University of Vienna
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Tutorial Material

Praktikum:
Helium-Neon Laser

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Quantenoptikpraktikum: A guide to the Helium-Neon Laser Setup

Goal of the experiment is to build and to characterize a Helium-Neon laser.

Particular components available to you are a gas-filled tube with a flat high reflectivity mirror, a second high reflectivity mirror, a high voltage source, a commercial He-Ne laser for alignment, and a Fabry-Perot interferometer for characterization.

Relevant Knowledge:

1. Gaussian Beam Propagation:

   See A2 plus any standard optics textbook if needed (see also Wiki)

2. Basics of Optical Cavities and Fabry Perot Interferometers:

   See A1 Stability Criterion (concerns transversal mode) and for the longitudinal modes, see any standard optics textbook (see also Wiki).

3. Working Principle of the Helium-Neon laser:
   See A3 for some safety instructions. Also Wiki article can serve as a good source for the working principle.

Tasks during the Experiment:

<u>1. Reflectivity of the output mirror</u>:

For later use (see 4.4 Cavity Finesse) and before you set up the laser, you need to determine the reflectivity of the end mirror optical resonator for your laser that is not attached to the He-Ne-Gas Tube. It has a significantly lower reflectivity than the other mirror and therefore will be the mirror where the major part of the laser power is emitted.

Align the laser beam of the alignment laser to the power meter. Using a lens to focus the light onto the power-meter will help to always hit the same position on the power-meter, which reduces systematic errors, as the power meter shows slightly different values for different positions on the detector chip.

By inserting the mirror in the laser beam you can measure the transmitted light, or transmissivity, and determine the reflectivity assuming the mirror is loss free. Is the result independent of the direction the mirror is facing?

<u>2. Assembly of the Laser:</u>

For the laser, you need to build a Fabry-Perot cavity (FPC) that contains the gain medium – the gas-filled tube with a Brewster window on one side and a high-reflectivity mirror on the other is provided to you. To build the FPC, the two end mirrors need to be aligned such that the light can travel several times in reflection between the two mirrors and through the gain medium without hitting and apertures, i.e., without significant losses. To achieve that condition, it is helpful to perform a pre-alignment using the alignment laser that is also provided to you. The light transmitted through the Fabry-Perot cavity provides a good signal to align to, it is increased when the mirrors and gas tube are well-aligned.

To achieve sufficient control over the beam path of the alignment laser you need additional mirrors that allow precise steering of the beam in reflection. There are four degrees of freedom to align: tilt and translation of the beam axis both transversal directions. Therefore, a set of two mirrors (which you can tilt in two directions) are sufficient. It will be helpful initially set up the two mirrors roughly such that the beam travels parallel to the table plane and parallel to the table edge at the height where it hits the gas filled tube at the center of its mirror.

The flat end mirror of the FPC with the higher reflectivity is directly attached to the gas tube. It is convenient to mount this mirror facing the alignment laser. Two conditions need to be fulfilled at the same time before you set up the second mirror:

1) Orthogonal reflection of the alignment laser beam from the flat end mirror. That means the reflection from the flat end mirror should overlap the incoming beam from the alignment laser beam. Steer the mirrors such that this reflection is sent back to the alignment laser.
2) The beam transmitted through the gas tube is a nice spot, no ring. The rings are formed from multiple reflections of the thin glass tube the laser beam is passing through.

Once these conditions are fulfilled you can set up the second end mirror. Again there are two things to keep in mind for the pre-alignment.

1) The light from the alignment laser, which is passing through the first mirror and the gas tube, should impinge orthogonally on the second end mirror such the beam path is directly reflected back into itself.
2) A cavity mode can only exist, when the FBC is not too long (see stability criterion A1).

Maybe you find a nice trick to meet condition 1?

If you did all of the above perfectly, the laser should already start to work. To test if this is the case, just switch off the alignment laser and switch the power supply for the gas tube on. If your laser works already, you should see a sharp small spot of red light on a piece of paper behind the second end mirror, which has the lower reflectivity. If it already works, congratulations! You can try to make the spot brighter by very careful alignment of the second end mirror.

Typically, the laser doesn't work immediately. In that case don't worry and don't disassemble the setup immediately. Probably you're pretty close. If it is only about a tiny alignment of the second end mirror you might achieve the working conditions by slightly tilting the mirror and watching, when or if you see the little sharp red spot appearing. From the previous alignment with the alignment laser you should have a little bit of feeling for how much tilt might actually make sense for searching the sweet spot.

It still doesn't work? Before you go crosschecking your pre-alignment, switch the alignment laser on and try to align the second end mirror such that you start to see the spot transmitted through both end mirrors blinking a little. This is happening when the spatial conditions for a working cavity are met. The blinking appears because the frequency of the alignment laser only sometimes hits the resonance frequency of the self-build FPC.

If everyone tried for a few minutes you better check if all the conditions for pre-alignment above are met – maybe something is misaligned or someone hit one of the alignment lasers steering mirrors by accident. You also need to try to be even more careful with the pre-alignment from the beginning.

3. Measurements:

Once the laser is set up and running you can start to characterize it.

Hint: For measurements of power it will be useful to switch off other sources of light, as they are responsible for a background signal in the detection. It does make sense to take the value shown at your detector of power meter with the laser off once it is set up in the right place (the background light at the detector depends on its position and the direction it is pointing at!). This will enable you to subtract the background in the evaluation where reasonable.

Please also keep in mind that all measurements of distance with a ruler (e.g. the distance between the mirrors) are fairly imprecise.

4.1 Polarization

The goal here is to determine how well a linear polarization is emitted from the self-build laser and the direction of polarization relative to the table plane.

Insert a half-wave plate and a polarizer between the laser and the power-meter. Create a table of measurements that shows the transmitted power (mW) and the corresponding angle (°) in steps of 10°. Create a plot and fit a sinusoidal curve to the data. The visibility $V = \frac{P_{max}-P_{min}}{P_{max}+P_{min}}$ of the curve shows how well the light is linearly polarized. The higher the visibility is, the higher the polarization degree.

If we define light that is transmitted through the polarizer as horizontally polarized (0° polarization), what measurement could you still do to estimate the absolute value of the angle of polarization. Think, Measure, Estimate…

What determines the polarization of the laser light?

4.2 Free spectral range – longitudinal modes

FSR from the cavity length:

Calculate the value for the free spectral range from a direct measurement of the FPC $\nu_{FSR} = \frac{c}{2L}$ (with L: length of the resonator, c: speed of light). For a typical cavity (L >> wavelength of light) the free spectral range is the frequency difference between subsequent longitudinal modes.

The following two measurements rely on the emission of laser light at more than one resonance frequency of the cavity.

Spectral measurement of FSR with a reference cavity:

In your equipment is a complete Fabry-Perot-Interferometer (FPI) whose length can be changed via a piezoelectric crystal. The length of the cavity is linearly dependent on the voltage applied to the crystal. This voltage should be between -30V and 150V.

By applying a triangular signal to the FPI you can periodically change the length of this cavity, which has a FSR $\nu_{FSR,D} = 1GHz$. It is possible to scan the length to change the resonance frequency by more than 1 FSR. By monitoring the transmitted power versus the applied voltage with a photodiode (the power meter is too slow) on an oscilloscope you can determine the FSR of yourself made laser cavity. How?

Take care to find a good scanning speed. If the scan is too slow, the cavity length might drift during a single slope. If you scan too fast, the piezo-crystal will not be able to follow. The monitor output of the voltage amplifier allows you to determine whether you scanning to fast, as the amplifier will not be able to apply the expected voltage to the piezo-crystal in that case.

Determine the FSR of your laser with this method (the corresponding plot and evaluation should be in the protocol – you will also need this data for the task in 4.3).

Direct measurement of the FSR from the beat signal of the emitted spectral lines

Using a spectrum analyzer (if available) or the oscilloscope you can directly detect the beat signal between the two emitted spectral lines as a fast periodic intensity modulation with frequency $\nu_{FSR} = \frac{c}{2L}$.

4.4 Cavity Finesse

The cavity Finesse is a measure of the quality of the optical cavity. The mean number of roundtrips of a photon in the cavity is roughly F/π. It can be calculated by

$$F = \frac{\pi\sqrt{R}}{1-R} = \frac{\nu_{FSR}}{\Delta\nu_{1/2}}$$

$$Reflectivity\ of\ the\ (out-coupling)\ mirror$$

$$Linewidth\ of\ the\ cavity\ resonances$$

a.) Determine the cavity Finesse F from the reflectivity of the mirror that you have measured initially assuming the mirror attached to the gas-filled tube is perfect.

b) Use the data from the “Spectral measurement of FSR with a reference cavity” to determine the Finesse via the linewidth of the cavity resonances $\Delta\nu_{1/2}$ (FWHM, Full width of the peak at half the maximum height).

Compare and discuss the results.

<u>4.4 Gaussian beam – transversal mode shape</u>

The self-build laser emits a light field that is determined by the cavity mode shape, a TEM00 mode. When you look at the emitted light far away from the output mirror you will see that the beam is actually expanding – the divergence angle, however, is really small (paraxial approximation is good).

This type of laser beam is typically called a Gauss beam, due to the Gaussian transversal intensity profile. It is determined by two parameters (neglecting the direction of the beam), for example the divergence and the position where the radius of the beam (waist) is minimal. For a circularly shaped Gaussian beam, the whole intensity distribution all along the beam is determined by these two parameters

Your next task is to characterize the mode shape of the Gauss beam by determining those two parameters.

To do so, you need to determine the waist of the beam different positions along the beam. As we are talking about a Gaussian transversal intensity distribution, you need to take care of the definition of beam waist/radius in that case.

To determine the intensity profile at each position, you have a translation stage available, that you can mount a knife edge on. This will move the knife edge into the beam in defined steps to block parts of the laser. How can you determine the intensity profile of the laser from this type of measurement?

Plot the beam waist vs. the corresponding position. It makes sense to choose the positions as a distance relative to a sensible reference point. Which reference point would make sense?

4. Guidelines for your protocol:

1) During the whole protocol: Cite whatever is not your own!
2) Describe your complete setup, how you build it and how you aligned it. Imagine someone who should repeat the experiment with the same equipment as efficiently as possible has only your protocol to do it.
    a. For a description of your setup: Include a complete schematic, picture or both in order to allow you to describe your setup and the role of the different components (name them in the drawing and use the names consistently in the protocol).
    b. Describe the different steps in your alignment. What did you do – step by step. What relevant observations did you make that helped you to successfully set everything up. What tricks did you learn etc.

3) For the characterization of your setup and the different measurements. Again – anyone who has no other sources and who was not present at the experiment should be capable of understanding your results and drawing his own conclusions to compare them to yours.
    a. Describe what you did for each of the measurements
       Show the results. Include error bars wherever possible and explain how you derived them.
    b. Describe how you did the evaluation (e.g. fits and equations – what were the free parameters for the fit? where are the equations from? …) and show the results.
    c. Discuss the results. Are they consistent with your expectations (If you need to add a theory part to explain your expectations you may consider doing it in an extra section at the beginning)? Do the results make sense at all? Why or why not? Are they consistent with each other? Do you have additional ideas to crosscheck this?
       Are there any inconsistencies? What are the possible explanations? Is there anything wrong in the measurement or in the evaluation etc.?

A1 Stability Criterion

We define parameters for the two mirrors of the optical cavity $g_{1,2} = 1 - \frac{d}{R_{1,2}}$, where d is the cavity length (or distance between the mirrors) and R_i is the radius of curvature of the respective mirror i. A cavity configuration is called stable if it can guide a transverse electromagnetic mode (see Gaussian beam), in other words, if the a light field "fits" between the mirrors. Once can show that an optical cavity is stable if $0 \leq g_1 g_2 \leq 1$.

As mirror 1, which is attached to the gas tube, is planar in your case, $g_1 = 1$ and therefore the product $g_1 g_2 = g_2 = 1 - \frac{d}{R_2}$. As $g_1 g_2$ is negative for $d > R_1$, the cavity laser cannot work if your cavity is too long. The curvature of the end mirror that is provided to you is 25cm. Note that making it shorter is "safe" as the stability criterion is fulfilled.

A2 Gaussian Beam Equations

The following equations can be used to calculate the divergence angle θ_{div}, Rayleigh length z_r and the beam waist:

$$\theta_{div} = arctan(\frac{\omega_0}{z_r}) \approx \frac{\lambda}{\pi\omega_0}$$

$$z_r = \frac{\omega_0^2\pi}{\lambda}$$

$$\omega(z) = \omega_0 \sqrt{1 + (\frac{z}{z_r})^2}$$

In far field,

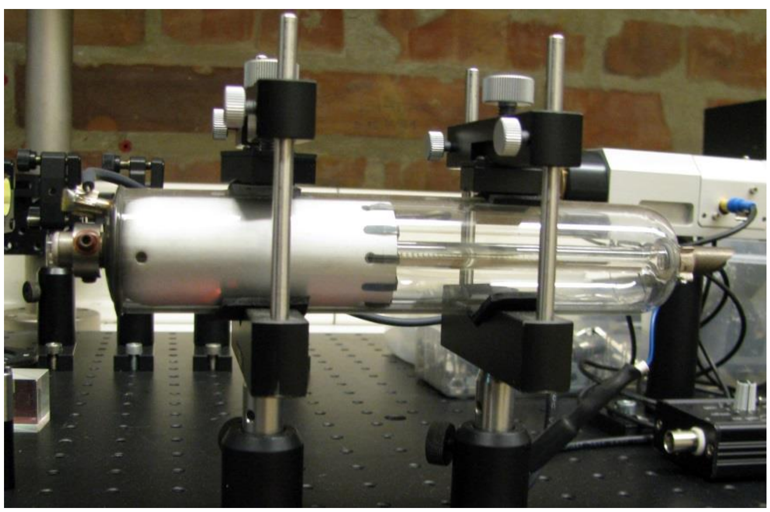
$$\lim_{z \to \infty} \omega(z) = \omega_0 \frac{z}{z_r}$$

λ *Wavelength of the laser*, z_r *Rayleigh length*, z *distance from the minimum beam waist*

A3 Gas filled tube and other main equipment

High voltage is applied to the gas filled tube that accelerates ions formed in the gas. Gas discharge within the tube excites helium atoms to a relatively long-lived state. They further collide with neon atoms, exciting some of them to a state that radiates 632.8 nm.

You need to be careful with the electrodes at the ends of the tube, as you might easily break a contact. Be even more careful not to touch the electrodes when the power supply is on and they are on high voltage.



Gas-filled tube with the cavity mirror (left) glued to one end and the Brewster window (right)

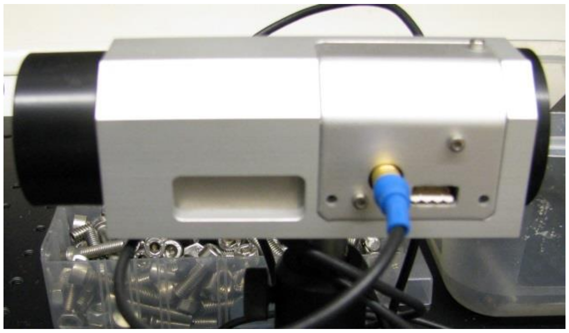
Do not touch the surface of the optics, your finger print can scatter light and drastically reduce the optics performance. If you accidentally touch them, please do not attempt to clean them yourselves. Call the tutor.

A4 Beat Signal

A beat signal is basically the equivalent of "interference fringes" in the time domain. When you overlap two coherent waves (i.e. their relative phase is fixed) of different frequencies, the total intensity will not only be the sum of two intensities, but it will be modulated in time with their difference frequency:

$$|E_1e^{i\omega_1 t} + E_2e^{i\omega_2 t}|^2 = {E_1}^2 + {E_2}^2 + 2E_1E_2\sin(\omega_1 - \omega_2)t$$

As the self-made He-Ne laser emits typically at least two optical frequencies with a difference frequency of the FSR, a beat signal can be observed.



Fabry-Perot Interferometer (FPI)

HV Amplifier for controlling the piezo-crystal inside the FPI