INSTRUCTIONS TO STUDENT

Helium Neon Laser

Aspects:
Laser resonator, stability conditions, high order modes, wavelength tuning.

Theory to be studied before the practical session:

Equipment:
• Helium Neon discharge unit with Brewster windows and power supply
• Concave high reflecting mirrors:
  radius of curvature: 500mm, 750mm, 1000mm, plane
• Concave 98% reflecting outcoupling mirrors:
  radius of curvature: 500mm, 750mm
• Adjustable horizontal and vertical mounted wires for transverse mode selection
• Quartz plate for wavelength selection
• HeNe laser for resonator alignment
• Spectrometer for measuring the laser wavelength.
• CCD camera to monitor the beam profile.
• Power meter to monitor the laser power (not available at the moment).
• Optical rail 2m length, mirror holders, alignment diaphragms
• Matlab program to calculate resonator properties

Introduction (set-up)

![ Helium Neon laser set-up ]

In general, a LASER (Light Amplification by Stimulated Emission Radiation) consists of a gain medium and two mirrors at each side of it. The mirrors are aligned precisely such that an optical resonator similar to a Fabry Perot interferometer is formed. The mirrors can be concave, plane or convex and one of the mirrors is made partially transparent to allow light to propagate to the
outside world as a well collimated, coherent, almost monochromatic beam. The gain medium can amplify light based on the principle of stimulated emission. Most, well designed, lasers emit the radiation as a beam concentrated around the optical axis with a Gaussian intensity profile, the fundamental TEM$_{00}$ transversal mode. This mode is desired for most applications using laser light. Under some conditions, however, a laser can be forced to operate on higher order transverse modes, indicated by TEM$_{m,n}$. One of the conditions is that the gain medium has a sufficient large bore compared to the beam diameter because these modes have a larger cross section than the fundamental mode, TEM$_{0,0}$.

![HeNe discharge tube with Brewster windows](image)

Figure 2 HeNe discharge tube with Brewster windows

Normally a laser will oscillate at the wavelength having the largest gain. By introducing wavelength depended losses in the resonator, however, a laser can be forced to oscillate on weaker lines.

With the HeNe laser discharge laser tube the student can study a number of fundamental laser properties: resonator stability conditions, high-order transversal modes and wavelength selection. By using mirror combinations with different radii of curvature and varying the length of the resonator the stability criterion can be investigated. Also by selecting mirrors and distance such that a very small beam size is obtained inside the discharge tube, a condition can be obtained where multi-transversal mode oscillation is possible (See Hecht p. 592). A particular mode can be selected by adjusting a vertical and horizontal thin wire into the resonator.

Other wavelengths than the strong 632.8 nm transition can be forced to oscillate by the insertion of a birefringent quartz plate in the resonator. The plate is positioned at the Brewster angle to minimize its losses and than rotated to vary the optical length of the resonator. In this way the frequency of a longitudinal mode (see Hecht p. 591) can be tuned such that is coincides with the centre of a particular (weak) transition while other (stronger) transitions are off-resonance. The discharge tube has Brewster windows at both ends. Because the laser will oscillate at resonator modes with the lowest losses the output beam is linear polarized.

Assignments

**Warnings:** The laser will emit at 632 nm less than 5 mW (under best conditions about 3.5 mW) which means that it is a class 3A laser. USE PROTECTIVE EYEWEAR.
NEVER look directly into the beam even while wearing protecting glasses. Be careful with reflections from mirrors and other reflecting objects. Arrange your set-up such that all reflections are in the horizontal plane.

Be very careful with the mirrors and other optics. Do not touch them with your fingers or un-mount them from the mirror holders.

Alignment of the laser

- Verify that the Helium Neon discharge unit has been placed on the rail at about 1 m from the side (left side) closest to the wall. Never remove the discharge unit from the rail, only shifting on the rail is permitted. Leave the discharge unit off for the moment.
- Do not place the adjustable wires and quartz plate.
- Place the alignment laser as far as possible at the opposite side (right side) of the rail. The laser beam should be directed to the wall and NOT to the laboratory room.
- Adjust the alignment laser in vertical and horizontal direction as well as its angle such that the beam goes through the discharge tube without hitting its inner wall. Use the CCD camera.
- Place one of the high reflecting mirrors (start with the R=750mm mirror) at the left side of and close to the discharge tube, adjust it such that the laser spot of the alignment laser is at the centre of the mirror and let the beam reflect through the tube and coincide precisely with the beam leaving the alignment laser. Placing a diaphragm in front of the alignment laser will help.
- Place one of the outcoupling mirrors (start with the R=750 mm outcoupler) close to the right side of the discharge tube. Adjust this mirror such that the beam reflected from the back side of this mirror goes exactly through the diaphragm in front of the alignment laser. Switch-on the discharge unit. If you are lucky the laser starts emitting immediately. If not, carefully adjust the mirror with small steps in vertical and horizontal direction until the laser starts. The laser oscillates if bright spots are visible on the left and right mirrors. These spots are caused by scattering of the intense intra cavity radiation at the mirror surfaces. Optimize the mirror alignment until these spots have maximum brightness.
  If you cannot get the laser to oscillate you can try the following: loose the screw which locks the slider to the rail. Then while rotating the mirror horizontally by rotating the slider, change the vertical mirror adjuster in small steps until you see a red spot blinking on the mirror surfaces. Lock the slider and vary the horizontal adjuster until the bright red spot appears.
- Now you can change the length of the resonator by moving one or both mirrors. Do this with small steps. Readjustment may be necessary, depending on how good you did the initial alignment.
- At optimum conditions, the laser will produce about 3.5mW output power. This means that, using an outcoupler with 98% reflectivity, there is a power of \(3.5/(1-0.98)\text{mW}=175\text{mW}\) inside the resonator. If you look at a small angle to the laser you can see this high power beam between the mirrors due to scattering from small dust particles. Sometimes people perform experiments inside the resonator to make use of the high power.

Experiments (to be performed in agreement with the supervisor)
• Check the stability conditions (see appendix) of the laser for the given sets of mirrors. Finish the table below and try a few mirror pairs (two) to test the stability condition.

<table>
<thead>
<tr>
<th>R₁ [mm] refl. ~100%</th>
<th>sticker color</th>
<th>R₂ [mm] refl = 98%</th>
<th>sticker color</th>
<th>stable if L [cm] is:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000 blue</td>
<td>500 red</td>
<td>0 &lt; L &lt; 50 or 100 &lt; L &lt; 150</td>
<td></td>
<td></td>
</tr>
<tr>
<td>750 orange</td>
<td>500 red</td>
<td></td>
<td></td>
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<tr>
<td>500 yellow</td>
<td>500 red</td>
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<tr>
<td>∞ yellow-white</td>
<td>500 red</td>
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<tr>
<td>1000 blue</td>
<td>750 green</td>
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<td>750 orange</td>
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<td>∞ yellow-white</td>
<td>750 green</td>
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</tbody>
</table>

• Use the Matlab program (appendix) to find out which resonator configuration will produce the most output power in the Gaussian TEM₀₀ mode. This will be the case if there is optimum overlap of the gain medium (in our case about 1 mm diameter) with the mode. Also choose a resonator configuration that will result in low output power. Build both resonators and compare them.

• The laser can oscillate on a high order transversal mode if the mode fits in the gain medium. A well-designed laser will only oscillate on the TEM₀₀ mode. This is the case if the diameter of the gain medium is just large enough for the TEM₀₀ mode. The higher order modes have larger sizes, will not fit and as a consequence will have higher losses. Multi mode oscillation can be obtained with our set-up by choosing a pair of mirrors and separate them at a distance such that the TEM₀₀ mode will have an as small as possible diameter (or beam waist, see appendix) in the gain medium. In that case the high order modes will experience sufficient gain to oscillate. If so, the spot size of the beam is larger than normal and dark and, bright spots in the mode pattern are visible because of interference. The mode pattern is very sensitive for the alignment of the mirrors. Usually a few higher order modes seem to oscillate simultaneously. In most cases the laser hops continuously from mode to mode due to small variations in the alignment (due to vibrations, temperature changes, etc). As you can see in Hecht, a high order mode has

![Figure 3](image_url)
dark and bright spots. A trick to select one particular high order transversal mode is to place a thin obstacle in such a dark area. Try this by first building a resonator which permits oscillation on multi transversal modes and select a high order mode by adjusting a thin wire placed inside the resonator.

Wavelength tuning
The HeNe can, in principle, be tuned to the wavelengths: 640.1 nm(4,3), 635.2 nm(1,0), 632.8 nm(10,0), 629.4 nm(1,9) and 611.8 nm (1,7). The relative strengths of the transitions is given between the brackets. Without any tuning element the laser will generate output at the strongest transition, at 632.8 nm. With a tuning element inside the resonator, losses can be introduced for all wavelengths except one. Tuning elements could be reflection gratings, prisms, mirrors with narrow-band reflection coatings and birefringent materials like calcite and natural quartz (Hecht chapter 8). In this exercise we tune the laser with a ~1 mm thick natural quartz plate positioned at the Brewster angle (also called: “polarization angle”) for minimum loss.

Figure 4 With a birefringent crystal (natural quartz) wavelength tuning is possible.

The optical axis is parallel to the plate. With such a plate the polarization of the light entering the plate can be changed by rotating the plate. However, at certain angles the polarization will not be changed and the losses will be minimal. Because the refractive indices depend on the wavelength the angle can be used to tune the laser. Follow the steps below to set-up a tunable HeNe laser.

• Align the laser with the two 750mm radius mirrors.
• Remove the outcoupler and rotate the alignment laser around its axis until the reflection from the Brewster windows is zero. Now the linear polarization of the alignment laser is horizontal.
• Place the quartz plate at the right side of the discharge tube. You can see two spots reflected from this plate. One is from the front surface, the other from its back surface. The spots are very close to each other. Rotate the quartz plate around the vertical axis until the reflection from the front surface is zero. Now the quartz plate is at the Brewster angle. This angle should be about 57°.
• Next rotate the quartz plate around its horizontal axis until the reflection from the back surface is zero too. The reflection from the Brewster plate on the discharge tube will be zero as well. Now the quartz plate causes minimum losses for the wavelength of the alignment laser, which is 632.8 nm. The losses are minimal because the polarization is
rotated 360° and as a consequence, the polarization of the beam exiting the plate is again horizontal. You can find a large number of angles where this is the case.

- Place the outcoupling mirror back and you should get laser output again at 632.8 nm.
- Optimize the output by rotating the quartz plate around the horizontal axis and the vertical axis. Find the optimum by iteration of both rotations. Maybe you must also do some adjustments of the mirror mount, because the beam is a little tilted by the plate.
- Use the spectrometer to measure the spectrum.
- Now you can tune the laser to another wavelength by rotating the quartz plate around the horizontal axis. The second strongest transition: 640.1 nm can be selected by this. Unfortunately the wavelengths of the weaker transitions cannot oscillate with our set-up.
Appendix. Resonator theory

Here a brief overview of the resonator theory is given. More details can be found in: “Lasers”, A.E. Siegman and “Optics”, E. Hecht.

A Gaussian TEM$_{00}$ beam at its beam waist can be characterized by its amplitude, $u_0$, and beam size (defined as the 1/e radius), $w_0$. At the beam waist the size of the beam is smallest and the radius of the wavefront is infinitive (i.e. it has a plane wavefront). In formula:

$$u(r) = u_0 e^{-\left(\frac{r}{w_0}\right)^2}$$

The intensity of the beam is proportional to the square of the amplitude and can be written as:

$$I(r) = I_0 e^{-2\left(\frac{r}{w_0}\right)^2}$$

When a Gaussian beam propagates in the $z$ direction from its waist at $z = 0$ to a point $z$, it can be shown that the radius of its wavefront is given by:

$$R(z) = z + \frac{z_R^2}{z}$$

Where $Z_R$ is the Rayleigh range (See Hecht: 13.18)

In a resonator with two mirrors positioned at $z=z_1$ and $z=z_2$ respectively, the radii of the wavefronts at the mirrors must be equal to the radii of curvatures, $R_1$ and $R_2$ respectively, of the mirrors. The size of the beam inside the resonator can thus be found by solving:

$$R(z_1) = z_1 + \frac{z_R^2}{z_1} = -R_1$$

$$R(z_2) = z_2 + \frac{z_R^2}{z_2} = R_2$$

$$L = z_2 - z_1$$

(1)
The minus sign in the first equation arises because of the sign convention used for mirror- and wavefront radii. We define the so-called g-parameters of the resonator:

\[ g_1 = 1 - \frac{L}{R_1} \]

\[ g_2 = 1 - \frac{L}{R_2} \] (2)

It can be found by solving (1) and using (2), that:

\[ z_R^2 = \frac{g_1 g_2 (1 - g_1 g_2)}{(g_1 + g_2 - 2 g_1 g_2)^2} L^2, \quad z_1 = \frac{g_2 (1 - g_1)}{g_1 + g_2 - 2 g_1 g_2} L, \quad z_2 = \frac{g_1 (1 - g_2)}{g_1 + g_2 - 2 g_1 g_2} L \]

\[ w_0^2 = \frac{L \lambda}{\pi} \sqrt{\frac{g_1 g_2 (1 - g_1 g_2)}{(g_1 + g_2 - 2 g_1 g_2)^2}} = \frac{\lambda z_R}{\pi} \]

\[ w_1^2 = \frac{L \lambda}{\pi} \sqrt{\frac{g_2}{g_1 (1 - g_1 g_2)}}, \quad w_2^2 = \frac{L \lambda}{\pi} \sqrt{\frac{g_1}{g_2 (1 - g_1 g_2)}} \]

Where \( \lambda \) is the laser wavelength, \( w_1 \) and \( w_2 \) are the beam sizes at the mirrors, \( L \), is the distance between the mirrors, and \( w_0 \) is the beam waist at \( z = 0 \).

From the equations it can be seen that real solutions only exist if:

\[ 0 \leq g_1 g_2 \leq 1 \]

This is called the stability range of the resonator. Outside this range no beam can exist between the mirrors and hence no radiation will be emitted by the laser.
A Matlab program is available, which calculates the beam size inside the resonator for given laser wavelength, mirror radii and resonator length.

The width of the Gaussian TEM\(_{00}\) mode inside the resonator is plotted as well as the stability diagram in which the two red curves are for \(g_1g_2 = 1\). The M\(_1\) mirror is at the left side at \(z = z_1\) and the M\(_2\) mirror is at the right at \(z = z_2\). The beam waist is at \(z = 0\). The blue dot in the stability diagram indicates the resonator configuration given by \(L, R_1\) and \(R_2\). The blue dot should be inside the area defined by the red curves and the \(g_1 = 0\) and the \(g_2 = 0\) lines. If it is outside this area, the resonator is unconfined and no mode can exist.

Copy-paste the m-file listing below into your Matlab editor and run it.

```matlab
%##########################################################################
% Calculation of the size of the fundamental Gauss mode, TEM00, inside a stable resonator. See: "Lasers", A.E. Siegman, Chapter 19.
% Fred van Goor, 7-8-2008
%##########################################################################

% definition of units:
m=1; mm=1E-3*m; cm=1E-2*m; micron=1E-6*m;
s=1;

c=2.9979E8*m/s; % velocity of light in vacuum
lambda=0.6328*micron; % laser wavelength (HeNe laser)
L=120*cm; % resonator length
% radii of curvatures of concave mirrors. (For a convex mirror use a negative value):
R1=750*mm; % radius of curvature of mirror M1
R2=500*mm; % radius of curvature of mirror M2

% resonator g-parameters:

L = 1.2 m, R\(_1\) = 75 cm, R\(_2\) = 50 cm
\(g_1 = -0.6, g_2 = -1.4\)
g\(_1\) * g\(_2\) = 0.84
\(z_1 = -73\) cm, \(z_2 = 47\) cm
\(w_1 = 0.961\) mm, \(w_2 = 0.629\) mm
\(w_0 = 0.155\) mm, \(Z_R = 12\) cm
```
\[ g_1 = 1 - \frac{L}{R_1}; \]
\[ g_2 = 1 - \frac{L}{R_2}; \]

% Rayleigh range
\[ Z_R = \frac{\sqrt{g_1 g_2 (1 - g_1 g_2)}}{(g_1 + g_2 - 2 g_1 g_2)^2)} \cdot L; \]

\[ w_0 = \sqrt{\lambda Z_R / \pi}; \quad \text{Beam size at waist at } z = 0 \]
\[ z_1 = - g_2 (1 - g_1) L / (g_1 + g_2 - 2 g_1 g_2); \quad \text{position of mirror } M_1 \]
\[ z_2 = g_1 (1 - g_2) L / (g_1 + g_2 - 2 g_1 g_2); \quad \text{position of mirror } M_2 \]
\[ w_1 = \sqrt{\lambda L / \pi \sqrt{g_2 / (g_1 (1 - g_1 g_2))}}; \quad \text{Beam size at mirror } M_1 \]
\[ w_2 = \sqrt{\lambda L / \pi \sqrt{g_1 / (g_2 (1 - g_1 g_2))}}; \quad \text{Beam size at mirror } M_2 \]

%q-parameter at beam waist z = 0, see "Lasers", A.E. Siegman
\[ q_0 = 1i \pi w_0^2 / \lambda; \]
\[ N = 1000; \quad \text{number of points for the plot} \]
\[ z_{\text{inc}} = (z_2 - z_1) / (N - 1); \quad \text{increment of } z \]
\[ z = \text{zeros}(1, N); \quad \text{initiation of } z \text{ array} \]
\[ w = \text{zeros}(1, N); \quad \text{initiation of } w \text{ array} \]
\[ \text{for } i = 1:1:N; \]
\[ \quad z(i) = z_1 + (i - 1) \cdot z_{\text{inc}}; \quad \% \text{filling } z \text{ array} \]
\[ \quad q = q_0 + z(i); \quad \% \text{q-parameter after propagation a distance } \]
\[ \quad \text{from } z = 0 \]
\[ \quad w(i) = \sqrt{-\lambda / \pi / \text{imag}(1/q)}; \quad \% \text{beam size at } z(i) \]
\[ \text{end} \]

% Plot the results in a 2D plot:
\[ \text{subplot}(211); \]
\[ \text{if } \text{isreal}(w) \% \text{plot only if } w \text{ is real} \]
\[ \quad \text{plot}(z/cm, w/mm, 'r', z/cm, -w/mm, 'r'); \quad \% \text{Also plot the lower edge of the beam} \]
\[ \quad \text{xlim}([z_1/cm, z_2/cm]); \text{ylim}([-1, 1]); \quad \text{grid on}; \]
\[ \text{else} \% \text{if } w \text{ is not real the mode cannot exist in the resonator} \]
\[ \quad \text{text}(L/3/cm, 0.5, '! not confined!!', 'FontSize', 14); \]
\[ \quad \text{text}(L/3/cm, 0, \text{sprintf('g_1 * g_2 = %0.3g', g_1*g_2), 'FontSize', 12)); \quad \% \text{inform} \]
\[ \quad \text{the user of the glq2 product} \]
\[ \quad \text{text}(L/3/cm, -0.5, \text{sprintf('g_1g_2 must be: 0 < g_1 * g_2 < 1'), 'FontSize', 12)); \]
\[ \quad \text{xlim}([0, L/cm]); \text{ylim}([-1, 1]); \quad \text{grid off}; \]
\[ \text{end} \]
\[ \text{xlabel('z [cm]'); ylabel('w [mm]');} \]
\[ \text{title('TEM_0_0 beam size inside the resonator')}; \]

gg1l=zeros(1, N);
gg2l=zeros(1, N);
gg1r=zeros(1, N);
gg2r=zeros(1, N);
gg1b=-5;
gg1e=0;
gg1_inc=(gg1e-gg1b)/(N-1);
\[ \text{for } i = 1:1:N; \]
\[ \quad \text{gg1l(i)=gg1b+(i-1)\cdot gg1_inc;} \]
\[ \quad \text{gg2l(i)=1/gg1l(i);} \]
\[ \text{end} \]
gg1b=0;
gg1e=5;
gg1_inc=(gg1e-gg1b)/(N-1);
\[ \text{for } i = 1:1:N; \]
\[ \quad \text{gg1r(i)=gg1b+(i-1)\cdot gg1_inc;} \]
\[ \quad \text{gg2r(i)=1/gg1r(i);} \]
% Plot the stability diagram:

subplot(212);
plot(gg1l,gg2l,'r',gg1r,gg2r,'r',g1,g2,'.','MarkerSize',20);
axis equal;
xlim([-5,5]);
ylim([-5,5]);
xlabel('g_1'); ylabel('g_2');
title('Stability diagram');
text(6,4,sprintf('L = %0.3g m, R_1 = %0.3g cm, R_2 = %0.3g cm',L/m,R1/cm,R2/cm),'
VerticalAlignment','bottom','FontSize',8);
text(6,2,sprintf('g_1 = %0.3g, g_2 = %0.3g',g1,g2),'
VerticalAlignment','bottom','FontSize',8);
text(6,0,sprintf('g_1 * g_2 = %0.3g',g1*g2),'
VerticalAlignment','bottom','FontSize',8);
if isreal(w)
    text(6,-2,sprintf('z_1 = %0.3g cm, z_2 = %0.3g cm',z1/cm,z2/cm),'
VerticalAlignment','bottom','FontSize',8);
    text(6,-4,sprintf('w_1 = %0.3g mm, w_2 = %0.3g mm',w1/mm,w2/mm),'
VerticalAlignment','bottom','FontSize',8);
    text(6,-6,sprintf('w_0 = %0.3g mm, Z_R = %0.3g cm',w0/mm,ZR/cm),'
VerticalAlignment','bottom','FontSize',8);
end
grid on;