The helium-neon laser
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In this paper a detailed description of the physical properties of the helium-neon laser is presented. Aspects like the energy level scheme, broadening mechanisms and gain coefficient will be discussed in detail and/or calculated as example. In the end a short discussion of a recent experiment using a He-Ne laser and a back-of-the-envelop calculation of the output power of a typical He-Ne laser is given. This calculation leads to an optimum output power of 28.3 mW/m$^2$ for a typical 632.8 He-Ne laser.

I. INTRODUCTION

The helium-neon laser was one of the first lasers ever made. The physicist Ali Javan, William Bennett and Donald Herriott developed it in the same year as the first functioning laser ever was made (which was in 1960). However, the He-Ne laser differed from its predecessors because it was the first gas and truly continuous-wave laser. Javan et al.\textsuperscript{1} used the 1.152 $\mu$m transition of Neon in their demonstration, but nowadays almost all possible transitions have been explored. The most famous He-Ne laser is the typical 632.8 nm red-light laser, discovered by White and Ridged.\textsuperscript{2} The highest gain in the visible spectrum can be achieved with this transition and it is therefore the most used He-Ne laser.

Helium-neon lasers have been used a lot in scientific research, but because of the relatively low output power and advances in semiconductor diode laser technology most of them are replaced nowadays. They were even predicted to become obsolete twenty years ago, but luckily this prediction turned out to be wrong. He-Ne lasers are still manufactured a lot and are sold more than all other lasers together.\textsuperscript{3}

In this paper physical properties of the He-Ne laser will be discussed in detail. First of all a short introduction into gas lasers will be given after which we delve into Javan’s discovery. In the end a small calculation of the output power of the 632.8 nm transition and a discussion of a recent experiment on wheat seedlings which used a He-Ne laser will be given.

A. Lasers

A laser is a light source based on the optical amplification of stimulated emission (hence the acronym for laser: \textbf{L}ight \textbf{A}mplification by \textbf{S}timulated \textbf{E}mission of \textbf{R}adiation). Stimulated emission, which is the process where a photon induces an excited atom to emit a new photon identical to the incident one, was proposed by Albert Einstein in 1917 and is one of the three ways in which light can interact with atoms. Absorption and spontaneous emission, respectively the process where an atom in the ground state absorbs a photon and moves to the excited state and the process where an excited atom emits a photon and decays to the ground state, are the two other possibilities.

To obtain optical amplification, there have to be sufficient stimulated emission to overcome the absorption process. This is a rare property of a system, called population inversion, which can not be achieved in a thermal equilibrium. It is also impossible to obtain a population inversion with just two energy levels because the lifetime of a typical excited atom is too short (about $10^{-8}$ seconds). This means that the electron will drop back as fast as they can be pumped up. More energy level systems are needed as requirement for a laser. A typical helium-neon laser uses two helium and four neon energy levels and is therefore called a four-level laser. The energy level scheme will be discussed in more detail in section II.

B. Gas lasers

Most of the gas lasers use electrical discharge as exciting mechanism, but there are also experiments performed where the laser was driven by optical pumping mechanisms or excitation by chemical reaction.\textsuperscript{4} However, He-Ne lasers are no exception and the exciting mechanism is just an electrical discharge. The simplest form of such a laser is illustrated in Figure 1. A gas is placed in a long cylindrical tube connected to a voltage source for the discharge process and a pair of mirrors at the end of the tube to amplify the radiation.

An electrical discharge in a gas will lead to a lot of different interactions but not all of them ensure a population inversion. Which specific process is responsible depends on variables like the total pressure, the nature and

![FIG. 1. A schematic illustration of a gas laser driven by electrical discharge. The voltage source is used to excite the atoms in the gas discharge tube which will lead to a population inversion. On both ends of the tube a mirror is placed to amplify the radiation.](image-url)
THE HELIUM-NEON LASER

In a helium-neon laser the He atom is excited by an electrical discharge. Collisions of the second kind between helium and neon atoms ensure the required population inversion between the neon energy states. A second kind collision is a process where the energy of a metastable state of one gas lies very close to the energy of an excited state of another gas. An inelastic collision between the two different atoms will then provide a transfer of excitation energy. For the He-Ne laser this collision will look like this (where subscript ‘ex’ means the exited state and ‘gr’ the ground state):

\[ \text{He}_{ex} + \text{Ne}_{gr} \rightarrow \text{He}_{gr} + \text{Ne}_{ex} + \Delta E. \]

The transfer cross-section of the collision, which tells you how likely it is for this event to happen, will depend on the energy difference \( \Delta E \) and the velocity of the atoms (so the temperature of the gas mixture). For low pressure discharges used in most gas lasers, cross-sections of the order \( 10^{-16} \text{ cm}^2 \) can be obtained for energy differences of 0.025 to 0.050 eV (or \( \Delta E = 200 \) to 400 cm\(^{-1}\))\(^6\). For higher energy differences the cross-section of the collision may be considered negligible and collisions of the second kind are no longer sufficient to obtain a population inversion.

Transitions between one quantum state to another, like collisions of the second kind, are constrained by selection rules. An example is the Wigner Spin Rule\(^7\). This is a selection rule that applies to the collisions between helium and neon. Such a collision is only likely (note that it is not impossible) when the total spin of the system is conserved. So the two series \( |S_{He} + S_{Ne}| \) to \( |S_{He} - S_{Ne}| \) before and after the collision need a common term. Surprisingly, the transition between the helium and neon atom is one of the relatively rare collisions where this rule is violated. The spin of the excited helium atom is 1, where the spins of the three other states are 0, so spin is not conserved.

A selection rule which is not violated and needed for the He-Ne laser to work is the parity selection rule. This rule ensures that the excited helium atoms do not decay by electric dipole transitions to their ground state. A electric dipole transition requires a change in parity, but both He states have even parity, and a transition between these states is therefore highly forbidden. Because of this the excited energy levels are metastable and can be used to excite neon atoms.

There are also selection rules for the transitions in the neon atom itself, which have been calculated for \( l = 1, 2 \) and 3 using the j-l coupling scheme of Racah\(^8\). The rules for allowed transitions are \( \Delta j_e = 0, \Delta l_e = \pm 1, \Delta k_e = \Delta (j_e + l_e) = 0 \) and \( \Delta J = \Delta (j_e + j_e) = 0 \) or \( \pm 1 \) (where subscript ‘e’ means core and subscript ‘c’ excited electron).

A. Energy level scheme

Two of the energy levels of the excited helium atom lie very close to those of the neon atom and can therefore be used as driving mechanism to obtain a population inversion. These two combinations are the 2\(^1\)S\(_0\) He level with the 2p\(^5\)5s Ne level (3s\(_2\) in the more standard Paschen notation) and the 2\(^1\)S\(_1\) He level with the 2p\(^5\)4s Ne level (2s\(_2\)). The energy difference between these two levels is respectively 386 cm\(^{-1}\) and 313 cm\(^{-1}\), which is small enough for the cross-section to not be negligible\(^6\). Collisions of the second kind lead to a population inversion between the just enumerated neon states with the lower 2p\(^5\)4p and 2p\(^5\)3p energy levels (respectively 3p\(_4\) and 2p\(_4\)). Between these levels slow decays in the visible and infra-red will happen (lifetimes of the order \( \tau_2 \approx 110 \) ns). The two lower states decay by relative fast UV transitions to the 2p\(^5\)3s configuration \( (\tau_1 \approx 20 \) ns). The ratio of the two lifetimes \( (\tau_2/\tau_1) \) is therefore very favourable which ensures that the population inversion between the 3s\(_2\)/2s\(_2\) and 3p\(_4\)/2p\(_4\) states is maintained and lasing is possible.

For the 2p\(^5\)5s and 2p\(^5\)4s state relative fast decays via electric dipole transitions in the vacuum violet towards the ground state of neon \( (\tau_2 \approx 10 - 20 \) ns) are also possible. These transitions can destroy the population inversion which is needed for lasing, so a way to block them is needed. Fortunately a solution have been found by increasing the neon pressure. At pressures above 0.05 Torr the probability to reabsorb the emitted resonance radiation by neon atoms in their ground state is so high that these electric dipole transitions can be considered as fully blocked.

There exists also a possibility that the 2p\(^5\)3p configuration gets populated by electron impact with the 2p\(^5\)3s configuration. This is another problem which breaks down the population inversion, so a fast way is needed to destroy these metastable 2p\(^5\)3s states. This can be achieved by making at least one dimension of the cavity sufficiently small. In this case, the atoms in the 2p\(^5\)3s state will diffuse to the walls and return to the ground state of the Neon atom before they can interact with electrons.

So the He-Ne laser is based on a four level pumping scheme where the helium, which is the one who gets
pumped by electrical discharge, is only used to excite the neon atoms to the energy level where the laser transition occurs. This pumping scheme, in the Paschen notation, is illustrated in Figure 2. To obtain a high output power with these transitions, the He:Ne ratio has to be approximate 6:1 and a pressure-tube diameter of 3.6 Torr mm is needed.

When the electron density of the discharge is increased, the number of excited He atoms tend towards an saturated value. This is because the ionization of excited atoms by electron collisions will increase, which is a major destruction process for the excited atoms. A saturation value for the excited helium states has of course also consequences on the excitation rate of the Ne 3s and 2s energy levels. Unfortunately, little can be done to solve this problem.

B. Broadening mechanisms

A transition which is used in a laser is never perfectly ‘sharp’, the outgoing spectrum will always be broadened because the transition has a finite lifetime. However, this natural line width is mostly not the real limit. A broadening caused by the random movements of molecules in a gas, called the Doppler shift, has more impact. Also the pressure, which indicates the number of collisions, can broaden the spectrum. Each broadening process can be classified in two types. If the broadening mechanism is the same for each quantum emitter the broadening is called homogeneous, while the broadening is inhomogeneous when every emitter has a different broadening fluctuation.

The broadening of the He-Ne laser is depicted as a combination of a homogeneous curve from the natural line width of neon and a inhomogeneous part from the Doppler shifts. However, the increase in neon bandwidth due to the homogeneous part is quite small, so the transition spectrum of a He-Ne laser will be mainly inhomogeneously broadened. The FWHM value for this broadening is 1.5 GHz for the 632.8 nm transition (but only 315 MHz for the 3.391 μm transition).

C. Amplification

For a He-Ne laser to work amplification (also called gain), which is provided by stimulated emission in the gaseous helium-neon medium, is needed. The strength of this interaction is parametrized by the stimulated emission cross-section. The gain has to overcome the losses in the cavity (for example through diffraction at the mirrors, scattering in the medium or absorption of the photons by neon atoms) to reach a steady-state with a non-zero intensity. If this threshold is overcome, the intensity will grow with each passage through the cavity (for a 632.8 nm He-Ne laser this is about 2-4 percent per round-trip). However, this can not go on forever. The gain coefficient, which describes the growth of the spectral intensity of the beam, is a function of the intensity itself. At high intensities the increased rate of stimulated emission will reduce the population inversion. This is called gain saturation which leads to a saturation intensity.

I will now give three small calculations for the stimulated emission cross-section, gain coefficient and the saturation intensity. A He-Ne laser operating at 632.8 nm with a 60 mA discharge current, tube diameter of 6 mm, He-Ne mixture ratio of 7:1 and a pd of 3.6 Torr mm is used. The emission for this laser is dominated by Doppler broadening with a line width of $\Delta \nu_D = 1.5$ GHz ($\Delta \nu_H = 14$ MHz) and a transition probability of $A_{21} = 3.4 \cdot 10^9$ s$^{-1}$. The gain cross-section and the stimulated emission cross-section (also called homogeneous cross-section) can be calculated with respectively equation 1 and 2:

$$\sigma_{21}^D = \frac{\ln 2}{16\pi^3} \frac{\lambda_{21}^3 A_{21}}{\Delta \nu_D} = 3.4 \cdot 10^{-13} \text{ cm}^2,$$ \hspace{1cm} (1)

$$\sigma_{21} = \frac{\lambda_{21}^3 A_{21}}{4\pi^2 \Delta \nu_H} = 2.5 \cdot 10^{-11} \text{ cm}^2. \hspace{1cm} (2)$$

To calculate the gain coefficient the population inversion density $N^*$ is needed. Data can be found from which follows that $N^* \approx 10^9$ cm$^{-3}$ is a good approximation for a 632.8 He-Ne laser. The gain coefficient, $\alpha = N^* \sigma_{21}$, is therefore 2.5 m$^{-1}$.

To calculate the saturation intensity the recovery time $\tau_R = \tau_2 + g_2/g_1 (1 - A_{21} \tau_2) = 117$ ns is needed. This

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FIG. 2. The energy level scheme of the He-Ne laser in the Paschen notation. The helium atom is excited by electrical discharge and interact with the neon atom using an inelastic collision. The Ne atom gets excited by this collision towards discharge and interact with the neon atom using a inelastic interaction value for the excited helium states has of course also major destruction process for the excited atoms. A saturation value for the excited helium states has of course also consequences on the excitation rate of the Ne 3s and 2s energy levels. Unfortunately, little can be done to solve this problem.

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To calculate the saturation intensity the recovery time $\tau_R = \tau_2 + g_2/g_1 (1 - A_{21} \tau_2) = 117$ ns is needed. This
leads to an saturated intensity of:

\[
I_{\text{sat}} = \frac{hc}{\lambda_21 \tau_0 \sigma_{21}} = 1.0 \cdot 10^4 \text{W/m}^2. \tag{3}
\]

III. LASER CONSTRUCTION

The construction of a modern He-Ne laser operating at the 632.8 nm transition is indicated in Figure 3. A detailed description of all parts goes outside the scope of this paper, but a few things are still worth to mention.

Nowadays, the cavity mirrors are sealed directly on the ends of the discharge tube but this was not the case in the first He-Ne lasers. These were constructed with the mirrors external to the gas envelope which resulted, logically, in more losses per round-trip. To reach the gain threshold of the laser, the gas envelope needed to be closed with windows tilted at Brewster's angle. This led to a transmission of 100% for a certain polarization of the incident light. Using this mechanism the threshold was exceeded, however the output of the laser was completely plane polarized. With the cavity mirrors sealed on the ends of the gas tube, as in present-day He-Ne lasers, Brewster’s windows are not necessary any more and the laser output is unpolarized. It is still possible though to achieve linear polarized light by fitting in a Brewster window in the indicated box in Figure 3.

The mirrors of He-Ne lasers are curved in a stable, near-confocal arrangement. The right mirror is a high reflector with a coated mirror surface to obtain maximum reflectivity at the lasers wavelength. The radiation from other transitions is deflected by small angles at this mirror and can be absorbed afterwards. So only radiation with the right wavelength will oscillate and profit from the population inversion in the cavity. The typical lengths of the cavities of modern He-Ne lasers are 15 to 50 cm. Such a length allows two to eight longitudinal modes to oscillate in the cavity. The left mirror transmits 0.5 to 1% of the radiation, which means that the intensity in the cavity is up to 200 times more intense than the output of the laser.

For the laser to operate sufficiently, a pure mixture of helium and neon is needed in the gas tube. Because the laser is filled with only a small amount of gas (1 Torr = 1/760 atmosphere), this mixture can be easily ruined by leakage from outside the laser. To prevent this a getter is placed inside the laser. The material of the getter is available to chemically combine with unwanted molecules inside the cavity. Because helium and neon are noble gasses they do not interact with the getter and so the pure mixture is maintained.

A. Calculation of the output power

In this section a back-of-the-envelope calculation of the output power of a typical He-Ne laser is given. I will use the same laser as in subsection II C for which \( \sigma_{21}^D \), \( \sigma_{21} \), \( \alpha_0 \) and \( I_{sat} \) have already been calculated. The properties of the laser are summarized in Table I.

With the exception of the 3.39 \( \mu \)m, all helium-neon lasers are low-gain lasers. This makes the calculation of the output power considerably easier because we can assume that the right- and left-going beams (respectively \( I_+ \) and \( I_- \) in the cavity have a near-constant intensity. In equation form this assumption means \( I(z) = I_+(z) + I_-(z) \approx 2I_+(z) \approx 2I_+ \). Because the increase in intensity is small per round-trip, we can also assume that the gain coefficient does not change appreciably with position in the gain medium. The saturated gain coefficient \( \alpha_I \) is therefore not dependent on \( z \).

The total intensity of the right-going beam will grow according to,

\[
\frac{dI_+}{dz} \approx \frac{I_+(l_{\text{tube}}) - I_+(0)}{l_{\text{tube}}} = \alpha_I I_+. \tag{4}
\]

The round-trip gain is twice this value, so the fractional increase in intensity \( \delta_{\text{gain}} = 2\alpha_I I_+ \) with \( \alpha_I = \alpha_0/(1 + 2I_+/I_{sat}) \).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Value [Dimension]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>( \lambda_{21} )</td>
<td>632.8 nm</td>
</tr>
<tr>
<td>Discharge current</td>
<td>( I_{\text{discharge}} )</td>
<td>60 mA</td>
</tr>
<tr>
<td>Diameter tube</td>
<td>( d_{\text{tube}} )</td>
<td>6 mm</td>
</tr>
<tr>
<td>Length tube</td>
<td>( l_{\text{tube}} )</td>
<td>30 cm</td>
</tr>
<tr>
<td>Mixture He:Ne</td>
<td></td>
<td>7:1</td>
</tr>
<tr>
<td>Pressure x diameter</td>
<td>( pd )</td>
<td>3.6 [Torr mm]</td>
</tr>
<tr>
<td>Gain cross-section</td>
<td>( \sigma_{21}^D )</td>
<td>3.4 ( \cdot 10^{-13} ) [cm(^2)]</td>
</tr>
<tr>
<td>Stim. emiss. cross-section</td>
<td>( \sigma_{21} )</td>
<td>2.5 ( \cdot 10^{-11} ) [cm(^2)]</td>
</tr>
<tr>
<td>Gain coefficient</td>
<td>( \alpha_0 )</td>
<td>2.5 ( [\text{m}^{-1}] )</td>
</tr>
<tr>
<td>Saturated intensity</td>
<td>( I_{\text{sat}} )</td>
<td>1.0 ( \cdot 10^4 ) [W/m(^2)]</td>
</tr>
</tbody>
</table>

TABLE I. Properties of the used He-Ne laser.
FIG. 4. The output power of a 632.8 nm He–Ne laser versus the transmission coefficient \( T_2 \) using the values from Table I.

We can characterize the losses in the cavity after one round trip in a similar way:

\[
\delta_{\text{total loss}} = 1 - R_1 R_2 \exp(-2\kappa_L L_c) \\
\approx (A_1 + A_2 + T_1 + 2\kappa_L L_c) + T_2 \\
= \delta_{\text{loss}} + T_2
\]

with \( A \) the absorption and \( T \) the transmission coefficients and \( \kappa_L L_c \) representing the attenuation of the beams by scattering or other losses inside the cavity. Unfortunately I could not find these values for this kind of laser, so I will assume \( \delta_{\text{loss}} \approx 0.5 \).

Under steady-state conditions the round-trip gain must be the same as the round-trip losses: \( \delta_{\text{gain}} = \delta_{\text{loss}} + T_2 \). From this equation we can find the intensity of the right-going beam,

\[
I_+ = \frac{1}{2} I_s \left( \frac{2\alpha_0 L_{\text{tube}}}{T_2 + \delta_{\text{loss}}} - 1 \right),
\]

where the output power is simply \( P = T_2 I_+ A_{\text{mode}} \) with \( A_{\text{mode}} \) the cross-sectional area of the beam. We now can calculate the output power for different \( T_2 \) using the values given in Table I. This output power versus the transmission coefficient is plotted in Figure 4. At values of \( T_2 > T_{th} \approx 1.5 \) the losses in the cavity are too large and no laser oscillation can occur anymore. As this plots shows there is an optimum output coupling at \( T_{2,\text{opt}} = 0.224 \) which yields an optimum output power of \( P_{\text{opt}} = 28.3 \text{ mW/m}^2 \). This is approximate the same as is stated in the literature.

IV. EXPERIMENT USING A HE–NE LASER

I will now shortly discuss an experiment from 2014 which used a He-Ne laser. As I already said in the introduction, most He-Ne lasers are replaced by semiconductor diode lasers and unfortunately I could not find a physics related paper using this laser. However, in other areas like for example plant biology the advances of He-Ne lasers are just being discovered. The paper I will discuss was published in Laser Physics and written by H. Chen and R. Han\(^1\). They explored the effect of continuous wave He-Ne laser radiation (632.8 nm and 5 mW/mm\(^2\)) on the physiological indexes of wheat seedlings at their early growth stages which are exposed to enhanced UV-B radiation (10 KJ m\(^{-2}\) d\(^{-1}\)). Because of the depletion of the ozone layer the level of UV-B radiation have increased in the last decades. This radiation has deleterious effects on the photosynthesis parameters in wheat (for example the chlorophyll content and electron transport rate). Chemical methods are used nowadays to protect the plants, but physical methods like He-Ne radiation can be more effective and beneficial.

The use of low power continuous wave He-Ne radiation have only been explored recently, but the results are already impressive. He-Ne radiation treatment has considerable biological effects on seed metabolism, enhances the drought stress resistance and helps accelerate seedling growth and development\(^1\). Furthermore it can help repair UV-B-induced damage and shorten the recovery time. It is therefore a very interesting and promising subject to study.

The authors of this paper examined the effects of the He-Ne laser treatment on the photosynthesis of wheat seedlings. After selecting representative seedlings, four different treatments were performed. The control group (group CK) with no radiation, the single enhanced UV-B treatment (B), He-Ne laser treatment (L) and finally the combined UV-B and He-Ne radiation treatment (BL). Some of the results are shown in Figure 5 and 6. After treatment of only the enhanced UV-B radiation, the chloroplast membrane was damaged, the content of chloroplast proteins were reduced and the activities in the CF1 ATPase and the Hill reaction were significantly reduced compared to the control group. For the combined UV-B and He-Ne laser group, these values were near the ones of the control group, and for the L group all parameters were improved.

So for all investigated parameters the trend was as follows: L > CK > BL > B. The authors therefore con-
cluded that He-Ne laser irradiation stimulated the activities of key enzymes and altered various parameters involved in wheat seedling photosynthesis. Single He-Ne laser radiation improved the parameters, while the combined He-Ne with UV-B radiation exhibited rehabilitation effects. When He-Ne laser radiation keeps showing positive effects in further research, it could be an interesting replacement for the chemical methods.

V. BIBLIOGRAPHY