The Helium-Neon laser

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Abstract

In this paper an overview will be given of the general working principles of the helium-neon laser. After a short introduction, the construction of the laser will be discussed as well as a the relevant energy levels and transitions. Up next are the broadening mechanisms and both the longitudinal and transverse modes. The paper will be finish with a back-of-the-envelope calculation of the output power and a short discussion of a recent experiment using a He-Ne.

1 INTRODUCTION

The helium-neon (He-Ne) laser was the first gas laser to be developed. The first He-Ne was constructed by Javan, Bennet and Herriott of Bell Telephone Laboratory in 1960 and operated at the 1.152 μm transition of neon, in the infrared spectrum. Lasers operating in the visible spectrum were however much more in demand, so soon many other neon transitions were investigated and about a dozen of visible transitions (and many more infrared transitions) in the neon atom have since been identified. The 632.8 nm transition turned out to have the highest gain in the visible spectrum and most He-Ne's operate on this transition. This paper will focus on the 632.8 nm transition, but the results can easily be adapted for other lasing transitions.

The He-Ne has been used for many applications, such as holography, barcode scanning, biological cell counting, printing and many other scientific, industrial and medical applications. Advances in the field of semiconductor diode laser technology have reduced the usage of the He-Ne significantly, but as the discussion of a recent experiment at the end of this paper will show, it still has some useful applications today.

In this paper, I will fist discuss the general working principles of a He-Ne and finish with a back-of-the-envelope calculation of the output power and the discussion of a recent experiment using a He-Ne. At the end of the paper some references are provided on which this paper is largely based.

2 CONSTRUCTION

Figure 1 shows a basic diagram of the construction of a He-Ne. The low pressure helium-neon gas mixture is contained inside a glass envelope. Inside this envelope is a small capillary bore tube. Electrodes are located at both ends of the tube. A high voltage of typically 1-5 kV is applied to these electrodes, causing a discharge current of typically 10 - 50 mA which acts as a pump source.

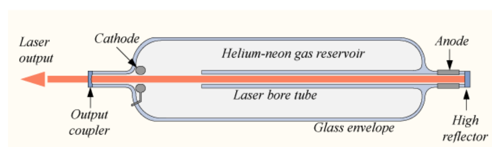

Figure 1: *Construction of the He-Ne. A helium-neon gas reservoir acts as a gain medium, whereas a high voltage applied to the two electrodes at the end of the discharge tube provide a discharge current which acts as a pump source. Mirrors are placed on both ends of the tube acting as a cavity. One of the mirrors has a reflection coefficient of typically 99%, allowing some of the laser light to exit the laser. Figure taken from [1]*

The optical cavity usually consists of two mirrors in a stable, near-confocal arrangement. One mirror would be coated to obtain maximum reflectivity at the desired wavelength (typically 99.9%) and the other with a transmission of 0.5-1%. This way, one of the spatial modes will reflect back upon itself and will gain more power in each roundtrip than is lost due to output coupling and diffraction. When the power keeps increasing it will at some point saturate resulting in a stable continuous laser beam output. Because He-Ne's are small gain lasers, it is essential that the mirrors are highly reflective in order to achieve lasing action.

The cavity length of the He-Ne usually ranges from 10 - 50 cm, while optical output powers range from 0.1 - 40 mW. These output powers are relatively small compared to other lasers.

3 ENERGY LEVELS AND TRANSITIONS

The basic principle of the He-Ne is based on a gas mixture of helium and neon that acts as a gain medium. Typical helium to neon ratios are of the order 7:1. A high voltage electrical discharge acts as a pumping source to excite the helium atoms. The helium atoms in turn will provide selective excitation to the upper levels of the neon atoms through resonant energy transfer.

A closer look at the discharge current and gain medium is needed to understand the working principles of the He-Ne, which is a four-level system. The electrons in the discharge current undergo inelastic collisions with helium atoms in the helium-neon gas mixture, causing these atoms to be excited from the ground state $1^1\mathrm{S}_0$ to the metastable states $2^3\mathrm{S}_1$ and $2^1\mathrm{S}_0$. The energies of these states are 19.81 eV and 20.61 eV respectively. These states are metastable, since a radiative transition to the ground state is forbidden by the parity selection rule.[1] The helium atoms thus only decay by collisions with the walls and neon atoms.

The transition used for lasing is a transition of the neon atom. In fact, it is possible to develop a neon-laser, without the helium, but this is much more difficult. As it turns out, coincidentally the neon atom has two energy levels that are very close to the two mentioned metastable states of helium. The $2^3\mathrm{S}_1$ level of helium lies within 313 cm^{-1} of the $2\mathrm{s}_2$ level of neon and the $2^1\mathrm{S}_1$ level of helium lies within 386 cm^{-1} of the $3\mathrm{s}_2$ level of neon. The $2\mathrm{s}_2$ level has an energy of 18.7 eV, whereas the $3\mathrm{s}_2$ level has an energy of 20.66 eV. To describe the neon energy levels it is common to use the Paschen notation instead of the term notation, so I will follow this convention here. When the helium atoms collide with the neon atoms these can be excited through resonant energy transfer. The small difference in energy or order 0.05 eV is provided by the kinetic energy of the atoms. In terms of reactions:

$$\mathrm{He}(2^3\mathrm{S}_1) + \mathrm{Ne}_{\mathrm{g.s.}} \to \mathrm{He}_{\mathrm{g.s.}} + \mathrm{Ne}(2\mathrm{s}_2) + 0.04\,\mathrm{eV} \quad (1)$$
$$\mathrm{He}(2^1\mathrm{S}_0) + \mathrm{Ne}_{\mathrm{g.s.}} \to \mathrm{He}_{\mathrm{g.s.}} + \mathrm{Ne}(3\mathrm{s}_2) - 0.05\,\mathrm{eV}$$

Since these thermal energy fluctuations obey a Maxwellian distribution, resonant energy transfer is much more likely to take place between levels with small energy differences than between levels with higher energy differences. The upper levels $3\mathrm{s}_2$ and $2\mathrm{s}_2$ are optically connected to the lower levels $3\mathrm{p}_4$ and $2\mathrm{p}_4$. In order to create a population inversion, selective excitation of the upper levels is needed. Both the upper and the lower levels are very high with respect to the ground state (the energy difference exceeds 18 eV). Therefore without pumping present these levels will essentially be empty. Because of the Maxwellian distribution, the resonant energy transfer is therefore selective in exciting pre-dominantly the upper levels of neon. Since both the upper and lower levels start with equal populations, any pre-dominance in populating the upper levels is sufficient to create a population inversion and therefore a relatively small pumping power suffices.

Figure 2 shows partial energy-level diagrams of the helium and neon atom, showing all the mentioned energy levels and transitions.

The coincidental closeness of the energy levels of helium and neon thus provides a mechanism for creating a population inversion through selective excitation. This is the main reason for including helium in the gas mixture.

The upper levels $3\mathrm{s}_2$ and $2\mathrm{s}_2$ can decay via transitions in the vacuum UV to the ground state, causing their radiative lifetimes to be relatively short (10-20 ns). To prevent the upper level from decaying to the ground state, a neon pressure above 0.05 Torr ($1\,\mathrm{Torr} \sim 133.3\,\mathrm{Pa}$) is used. At these pressures, the probability for the resonance radiation to be absorbed again by the ground state is so high that the transition can be regarded as fully blocked. The effective lifetimes of the levels $3\mathrm{s}_2$ and $2\mathrm{s}_2$ are therefore determiend by their much slower decay via visible transi-

[1] The parity of the wavefunction of all the energy levels is even (odd) when the sum of the l-values of all the electrons is also even (odd). The ground state of Helium is 1^1S_0, which has two electrons in the 1s orbital and thus $\sum_i l_i = 0$. In the states $2^3\mathrm{S}_1$ and $2^3\mathrm{S}_1$ one of the electrons has been promoted from a 1s orbital to a 2s orbital (the difference between the two states is the alignment of the spins). For these states we also have $\sum_i l_i = 0$. Electric dipole radiation requires a change of parity, which is not the case for this transition and the transition is therefore highly forbidden.

tions, giving them lifetimes of $\tau_2 \approx 136\,\text{ns}$ for $2s_2$ and $\tau_2 \approx 110\,\text{ns}$ for $3s_2$.

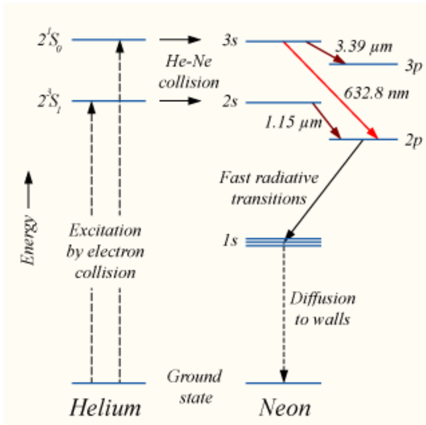

Figure 2: *Partial energy-diagrams of helium and neon. A discharge current excites helium atoms from the ground state to metastable states, which in turn excite neon atoms through resonant energy transfer. The neon atoms undergo a radiative transition to a lower level hereby transmitting laser light. Figure taken from [2].*

The lower levels $2p_4$ and $3p_4$ can decay by UV transitions to levels in the $1s_2$ - $1s_5$ manifold[2]. These UV transitions are relatively fast with lifetimes of the order of $\tau_1 = 20\,\text{ns}$.

For a steady-state inversion to exist, the following condition must be satisfied

$$\frac{R_2}{R_1}\frac{\tau_2}{\tau_1}\frac{g_1}{g_2}\left(1 - \frac{g2}{g1}A_{21}\tau_1\right) > 1. \quad (2)$$

What is relevant for this paper is only the factor τ_2/τ_1. A practical way to ensure this conditions is by making sure that all separate factors are larger than 1, which yields for the lifetimes the condition $\tau_2/\tau_1 > 1$. For the He-Ne we have $\tau_2/\tau_1 \approx 5$, which is very favourable.

The atoms in the $1s_2$-$1s_5$ cannot undergo a radiative transition to the ground state. Instead, they return to the ground state mainly by collisions with the walls of the discharge tube. The effect of this process is that the gain is inversely proportional to the diameter of the tube. Therefore the diameter of the tube is typically only a few milimeters.

[2]This multiplet nature of the neon energy levels is caused by the fact that the angular moment of the electrons can be combined in several different ways. [3]

4 BROADENING MECHANISMS

Broadening mechanisms can be divided into two categories: homogeneous and inhomogeneous. In the case of homogeneous broadening, all atoms in a specific energy level radiate with equal probability, whereas in the case of inhomogeneous broadening this probability fluctuates per atom.

Different forms of broadening exist, the most important of which are natural broadening, Doppler broadening and pressure broadening. Natural broadening is homogeneous and is caused by the finite lifetime of the transition. Because of natural broadening the gain curve always has a finite width. Natural broadening causes the gain curve to have a Lorentzian shape.

Pressure broadening is a type of homogeneous broadening, caused by the collisions of atoms with the emitting atom. Since the He-Ne is a low pressure laser, this effect is negligibly small.

Doppler broadening is caused by the different velocities of the emitting atom, which causes them to have different Doppler shifts and are thus observed to have different energies. Doppler broadening causes the gain curve to have a Gaussian shape.

In the case of the low-pressure He-Ne laser Doppler broadening dominates and therefore the shape of the gain curve is a Voigt distribution, which is the combination of a Gaussian and a Lorentzian. the deviation from a Gaussian is however very small. The He-Ne gain curve is relatively sharp with a full width of only 1.5 GHz for the 632.8 nm transition.

5 MODES

Both longitudinal and transverse spatial modes exist in the He-Ne laser. The long and narrow discharge tube forces the TEM00 mode to be present. Most He-Ne's operate in only this single transverse mode. Multimode He-Ne's do however also exist and can be constructed by using a wide bore, such that higher order modes also play a significant role.

Due to interference effects the laser resonator only supports output beams at specific, equally spaced frequencies (longitudinal modes) which are determined by the mirror spacing. The output of the laser is given by the frequencies in the intersection of these resonator modes and the laser gain curve. The number of longitudinal modes present in the He-Ne therefore depends on the cavity size. For a larger (smaller) cavity length, more (less) longitudinal modes will be present in the output beam. For cavities of lengths 15-50 cm about 2 to 8 longitudinal modes can oscillate simultaneously. He-Ne's operating at a single longitudinal mode are also available for special applications.

6 OUTPUT POWER

A short back-of-the-envelope calculation of the output power of a 632.8 nm He-Ne laser with the properties listed in Table 1 will be provided in this section. In a steady-state situation the gain and losses in a single round-trip must cancel each other. To achieve this, the contributions of the gain and the losses will be calculated separately, starting with the gain.

The intensity in the cavity is given by the sum of the left-travelling and right-travelling beams, with intensities I_+ and I_- respectively. He-Ne lasers are small gain lasers, with a typical roundtrip gain of 2-4%. Because the gain is so small, we can neglect the change of intensity with position z and thus approximate $I_+ \approx I_- \equiv I$. The total intensity in the cavity is therefore given by $I_{tot}(z) = I_+ + I_- \approx 2I$. The change in intensity in *half* a roundtrip is given by $\frac{\mathrm{d}I}{\mathrm{d}z} \approx g(\nu)I$, with $g(\nu)$ the gain coefficient. The fractional gain α_{gain} for a *total* roundtrip is then given by $\delta_{gain} = 2g(\nu)l_{tube}$.

For the losses in the cavity there are three different mechanisms that can contribute: diffraction losses, losses due to output coupling and losses due to finite conductivity. [4] In this calculation it will be assumed that the only non-negligible losses are due to diffraction and output coupling. The fractional loss is thus given by $\alpha_{loss} = \alpha_d + \alpha_{out}$, with $\alpha_{out} = T$ and $\alpha_d = 16\pi^2 N_F \mathrm{e}^{-4\pi N_F}$. [4] Here T is the transmission coefficient of the output coupling mirror and N_F is the Fresnel number. I will assume that the diffraction losses are very small and thus take for the Fresnel number $N_F = 1$.

Equating the expressions for α_{gain} and α_{loss} and using $g(\nu) = g_0(\nu)/(1 + I/I_{sat})$, with I_{sat} the saturation intensity, the intensity in the cavity can be calculated. Using $P = T \cdot A \cdot I$ to get the transmitted power we find

$$P = TAI_{sat}\left(\frac{2l_{tube}g_0(\nu)}{16\pi^2 N_F \mathrm{e}^{-4\pi N_F} + T} - 1\right), \qquad (3)$$

with A the area of the beam. For the area I assumed that the beam does not diverge much after exiting the tube, such that the area of the beam is just $\pi d_{tube}^2/4$. Equation 3 clearly shows the dependence of the output power on several relevant parameters. For increasing cavity lengths l_{tube}, the output power increases. He-Ne's are relatively small with cavity lengths of 10-50 cm and accordingly have small output powers of the order of tens of miliWatts. For increasing area, and thus increasing tube diameter, the power of the laser increases. A larger tube diameter allows for the presence of higher order modes in the ouput beam, which has the effect to increase the total power.

Figure 3 shows the resulting output power as a function of the transmission coefficient. A maximum is obtained for $T_{max} = 0.0076$ (0.76%) and $P_{max} = 20.3\,\mathrm{mW}$. The ouput power is in the range that is also stated in the literature. [5] Of course the height of the maximum depends on the properties of the specific laser. Most He-Ne's have a transmission of 0.5-1%, which is around this maximum value. For even smaller transmission coefficients, the output power decreases rapidly. For $T > T_{th} = 0.12$ the transmission is too large and lasing above this threshold is not possible.

For a certain value of the transmission T the output power can be optimized by enforcing the condition $p \cdot d_{tube} = 3.6\,\mathrm{Torr} \cdot \mathrm{mm}$ on the pressure in the laser p and the tube diameter d_{tube}.

It should be noted that many important parameters, such as the helium to neon ratio, the atomic lifetimes and the pump rate, are not taken into account in this calculation. For a more accurate result, a more extensive calculation is needed.

A consequence of the dependence of the output power on the cavity length and temperature fluctuations is the presence of output power fluctuations. Changes in the temperature affect the positions of the mirror, thus changing the cavity length. Due to the changed cavity length, the longitudinal modes sweep across the gain curve, causing oscillations in the output power. Longer lasers typically have smaller output fluctuations. A seven-inch-long laser will have output fluctuations of about 10%, while a fourteen-inch-long laser will have fluctuations of less than 2%. The fluctuations can be eliminated by completely stabilizing the temperature in the laser.

Wavelength	λ	632.8	(nm)
Tube length	l_{tube}	30	(cm)
Tube diameter	d_{tube}	2	mm
Small signal gain coef.	g_0	$2 \cdot 10^{-3}$	(cm^{-1})
Fresnel number	N_F	1	
Saturation intensity	I_{sat}	6.2	($\mathrm{W/cm}^2$)

Table 1: Properties of the He-Ne laser used for the output power calculation.

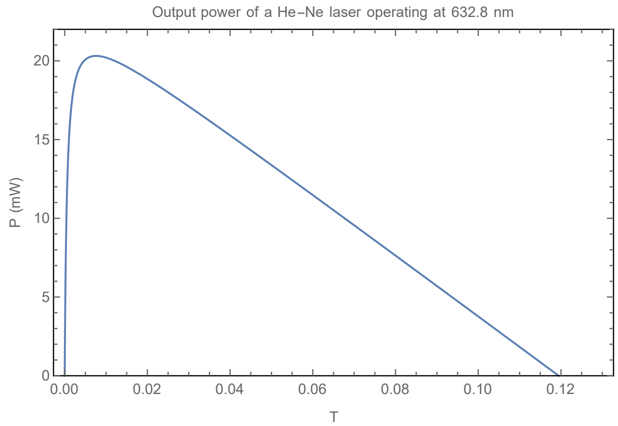

Figure 3: *The result of a back-of-the-envelope calculation of the output power of a 632.8 nm He-Ne laser. A maximum in the output power is obtained for* $T_{max} = 0.0076$ *(0.76%) at* $P_{max} = 20.3\,\mathrm{mW}$. *Above the threshold* $T_{th} = 0.12$ *lasing is not possible.*

7 USAGE IN EXPERIMENTS

As mentioned in the introduction, the He-Ne serves many applications both inside and outside of physics. An example of an application outside of physics is the usage of the He-Ne in cell biology research. One such example is a 2001 research on cell stimulation by He-Ne laser light by Grego et al. [6]. In this paper both the direct and indirect dependence of cells on light from a 632.8 nm He-Ne were studied. Photostimulation is procedure used in therapy of many different diseases. Research has shown that He-Ne laser light can stimulate a variety of biological processes, such as cell growth and proliferation. The paper gives insight into both the direct and indirect mechanisms by which He-Ne laser light can cause cell stimulation. A thorough treatment of the research by Grego et al. is beyond the scope of this paper, but the interested reader with a strong background in cell biology is encouraged to take a look at the references.

REFERENCES

[1] 20 April 2016. URL `https://upload.wikimedia.org/wikipedia/commons/a/af/Hene-1.png`.

[2] 20 April 2016. URL `https://upload.wikimedia.org/wikipedia/commons/e/ed/Hene-2.png`.

[3] 19 April 2016. URL `http://electron6.phys.utk.edu/phys250/modules/module%204/lasers.htm`.

[4] Ferrari A. Lofnes T., Ziemann V. Analytical design of a confocal resonator. *http://www.tsl.uu.se/digitalAssets/187/187392_1tslnote-2003-56.pdf*, 2003.

[5] Webb C.E. Hooker S. *Laser Physics*. Oxford: Oxford University Press, 2010.

[6] Moro L. Perlino E. Petragallo V.A. Marra E. Passarella S. Greco M., Vacca R.A. Helium-neon laser irradiation of hepatocytes can trigger increase of the mitochondrial membrane potential and can stimulate c-fos expression in a ca2+-dependent manner. *Lasers in Surgery and Medicine*, 2001.

[7] 18 April 2016. URL `https://en.wikipedia.org/wiki/Helium%E2%80%93neon_laser`.

[8] Yeh C. *Applied Photonics*. Academic Press, 1994.

[9] Freedman R.A. Young H.D. *University Physics with Modern Physics*. Pearson Education (US), 2004.

[10] Naidu S.M. *Engineering Physics-I*. Pearson Education (India), 2009.

[11] Swarup A. Khare P. *Engineering Physics Fundamentals And Modern Applications*. Jones and Bartlett Publishers, 2007.

[12] Jones J. Webb C. *Handbook of Laser Technology and Applications*. Institute of Physics Publishing, 2004.

[13] Willet C.S. *An Introduction to Gas Lasers: Population Inversion Mechanisms with emphasis on selective excitation processes*. Pergamon Press, 1974.

[14] 19 April 2016. URL `http://www.repairfaq.org/sam/laserhen.htm#henphlpo`.