V61

He-Ne Laser

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Contents

1 Objective

To understand the characteristics of a He-Ne laser, several different configurations are adjusted and their radiation properties measured. This includes the wavelength, intensity distribution, polarization, mode spectrum, as well as the influence of mirror type and resonator length.

2 Background [1]

Lasers are ubiquitous tools of modern physics due to their useful properties, characterized by the emission of coherent light with narrow spectral linewidth, low divergence and high power density. They are named after the acronym for light amplification by stimulated emission of radiation, describing the fundamental mechanism for the production of laser radiation. This will be explored in the following, both in the general as well as the special case of the He-Ne laser.

2.1 Components of a laser

The basic setup of a typical laser consists of three main components, namely an active medium, a pumping mechanism and the resonator cavity.

Inside the active medium, realized using materials such as semiconductors or gas mixtures, photons are emitted from atomic transitions to energetically lower states. The energy difference ΔE between the involved electron levels is therefore the main determinant of wavelength λ and frequency f via $\Delta E = hf$.

To excite electrons in the active medium to higher levels, an energy source is required. This is the role of the pumping mechanism, which can be implemented using electrons or photons. The latter case is called optical pumping, as another separate light source tuned to the respective ΔE value is used to induce transitions to excited states.

Amplification of the emitted radiation is achieved in the active medium. Instead of using superradiant lasers, which have high gain factors and divergence, or impractically long constructions, mirrors can be used to create a resonator cavity. The resulting standing waves correspond to multiple passes through the material and can generate a stable beam with low divergence, which can exit through a semitransparent window. The mirror geometry can be adapted to the desired function with flat or concave designs.

2.2 Processes in the active medium

There are three main processes shown in Figure 1 occuring inside the active medium to facilitate the operation of a laser.

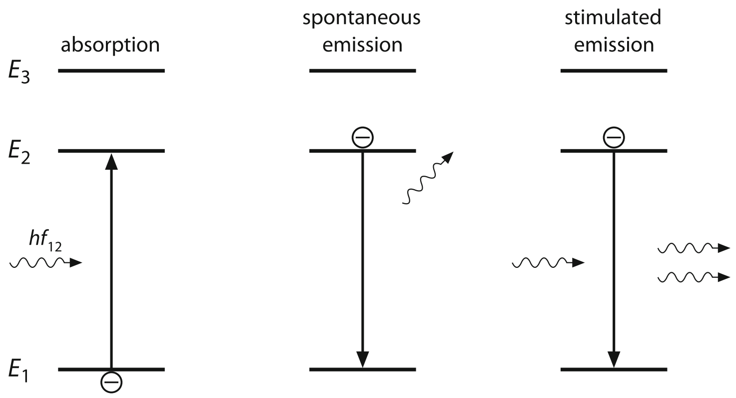

Figure 1: Schematic depiction of relevant processes inside the active medium. [1]

Raising the energy of an electron by $\Delta E = E_2 - E_1$ requires the annihilation of an incident photon that fulfills the condition

$$\Delta E = hf_{12} \, ,$$

where h is the Planck constant. This process is referred to as absorption. The number of transitions per time and volume is proportional to the density of ground state electrons N_1 as well as the photon flux or number per area and time φ via

$$\left.\frac{dN_1}{dt}\right|_{\mathrm{ab}} = -\sigma_{12} N_1 \varphi \, ,$$

with σ_{12} denoting the effective cross section for absorbing a photon. From this also follows the typical exponential intensity reduction

$$\left.\frac{dI}{dx}\right|_{\mathrm{ab}} = -\sigma_{12} N_1 I \, ,$$

where $\alpha = -\sigma_{12} N_1$ gives the absorption coefficient.

When an atom is in an excited state, it returns to the ground state after a time interval, the duration of which follows some random distribution with mean lifetime τ. Due to its stochastic nature, this process is called spontaneous emission and has no predefined direction or phase. The density in the higher level then follows

$$\left.\frac{dN_2}{dt}\right|_{\mathrm{sp}} = -\tau^{-1} N_2 \, .$$

Besides this, emission can also be initiated by an incoming photon of appropriate frequency. This is called stimulated emission and results in the production of radiation with the same energy, direction and phase as the inducing quantum. As the inverse process to absorption,

$$\left.\frac{dN_2}{dt}\right|_{\mathrm{st}} = -\sigma_{21} N_2 \varphi \,,$$

describes the time derivative and

$$\left.\frac{dI}{dx}\right|_{\mathrm{st}} = \sigma_{21} N_2 I \,,$$

the corresponding intensity relation. This means that stimulated emission leads to an increase in intensity, serving as a potential mechanism for amplification when there are more electrons in the excited state than in the ground state and losses are compensated for. This phenomenon in referred to as population inversion.

The cross sections can be identified with the Einstein coefficients B_{ij} via

$$\sigma_{ij} = B_{ij} h f_{ij} / c \,,$$

where c is the speed of light in vacuo. Furthermore, for emission and absorption, the thermodynamic or quantum mechanical relation

$$g_1 \sigma_{12} = g_2 \sigma_{21}$$

holds, with g_1 and g_2 defining the degrees of degeneracy for the ground and excited states. Hereafter, it is assumed that E_1 and E_2 have the same number of sublevels, so $g_1 = g_2$ for $\sigma_{12} = \sigma_{21}$ and

$$B \equiv B_{12} = B_{21} \,.$$

The reciprocal decay timescale defines another Einstein coefficient

$$A = \tau^{-1} \,,$$

with which the stationary spectral radiance

$$\rho_s \equiv \frac{A}{B} = \frac{8\pi h f_{12}^3}{c^3}$$

can be written. Introducing the general spectral radiance

$$\rho = \varphi h f_{12} / c$$

and requiring $N = N_1 + N_2$ to be constant for a system of two energy levels, one finds

$$\frac{dN_1}{dt} = \left.\frac{dN_1}{dt}\right|_{\mathrm{ab}} - \left.\frac{dN_2}{dt}\right|_{\mathrm{st}} - \left.\frac{dN_2}{dt}\right|_{\mathrm{sp}} = \rho B (N_2 - N_1) + A N_2 = -\frac{dN_2}{dt} \,.$$

For $\Delta N = N_2 - N_1$ then follows that

$$\frac{d\Delta N}{dt} = -2\frac{dN_1}{dt} = -2\rho B\Delta N - 2AN_2 + AN_1 - AN_1 = -2\rho B\Delta N - A\Delta N - AN\,.$$

After some time an equilibrium is reached inside the active medium, resulting in a vanishing time derivative. In this case, solving for the stationary number difference

$$\Delta N_s = -\frac{AN}{A + 2\rho B} = -\frac{N}{1 + 2\rho/\rho_s}$$

yields $\Delta N_s < 0$ for any system with only two energy levels.

2.3 Necessity of multiple levels

This result directly contradicts the requirement of population inversion $\Delta N_s > 0$ necessary for the amplification through stimulated emission as discussed previously, preventing the usage of two level systems as the active medium. Adding more energy levels as depicted in Figure 2 solves this problem. Instead of immediately relaxing back to the ground state via spontaneous emission, excited electrons now decay very quickly from E_3 to E_2 and E_1 to E_0 while the E_2 to E_1 transition takes longer. This means that $A_{21} < A_{32}$ as well as $A_{21} < A_{10}$ and results in a distribution similar to what is shown below.

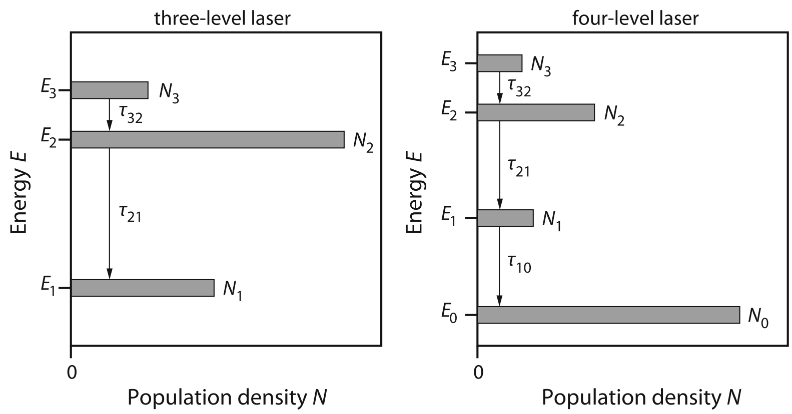

Figure 2: Exemplary energies and population densities for multiple levels. [1]

One then expects $N_0, N_2 \gg N_1, N_3$ for $N \approx N_0 + N_2$ and $\Delta N \approx N_2$ in the stationary configuration. Accordingly, a population inversion $\Delta N_s > 0$ is trivial to achieve, making four level systems a suitable choice for laser construction.

Such a system is realized by a He-Ne laser when the red mode at $\lambda = 633\,\mathrm{nm}$ is used. Table 1 indicates that this corresponds to a transition from the $3\mathrm{s}_2$ to the $2\mathrm{p}_4$ level, on which Figure 3 provides more detailed information.

Table 1: Properties for different transitions of the He-Ne laser. [1]

Color	Wavelength (nm)	Transition (Paschen notation)	Output power (mW)	Spectral width (MHz)	Gain (%/m)
Infrared	**3391**	$3s_2 \rightarrow 3p_4$	>10	280	10,000
Infrared	1523	$2s_2 \rightarrow 2p_1$	1	625	
Infrared	**1153**	$2s_2 \rightarrow 2p_4$	1	825	
Red	640	$3s_2 \rightarrow 2p_2$			
Red	635	$3s_2 \rightarrow 2p_3$			
Red	**633**	$3s_2 \rightarrow 2p_4$	>10	1500	10
Red	629	$3s_2 \rightarrow 2p_5$			
Orange	612	$3s_2 \rightarrow 2p_6$	1	1550	1.7
Orange	604	$3s_2 \rightarrow 2p_7$			
Yellow	594	$3s_2 \rightarrow 2p_8$	1	1600	0.5
Green	543	$3s_2 \rightarrow 2p_{10}$	1	1750	0.5

In this setup, the active medium is a mixture of helium and neon gases. Helium atoms are excited to metastable states via electric discharge before colliding with neon atoms to provide excitation and transfer kinetic energy via

$$\mathrm{He}^* + \mathrm{Ne} \longrightarrow \mathrm{He} + \mathrm{Ne}^* + E\,.$$

The excess energy $E \simeq 100\,\mathrm{meV}$ is dissipated as heat after the resonant transfer, as it measures about two times the 300 K thermal energy. Due to the selection rules, the upper 2s and 3s levels have lifetimes of the order 100 ns because they can only decay to p levels, while lower states exhibit shorter 10 ns timescales.

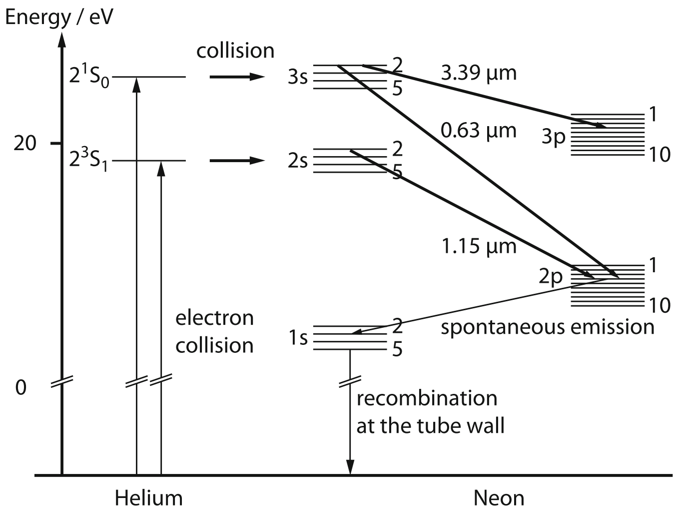

Figure 3: Energy level diagram of a He-Ne laser in Paschen notation. [1]

2.4 Stability for different resonators

$$g_k = 1 - \frac{L}{R_k}$$

$0 \leq g_1 g_2 \leq 1$

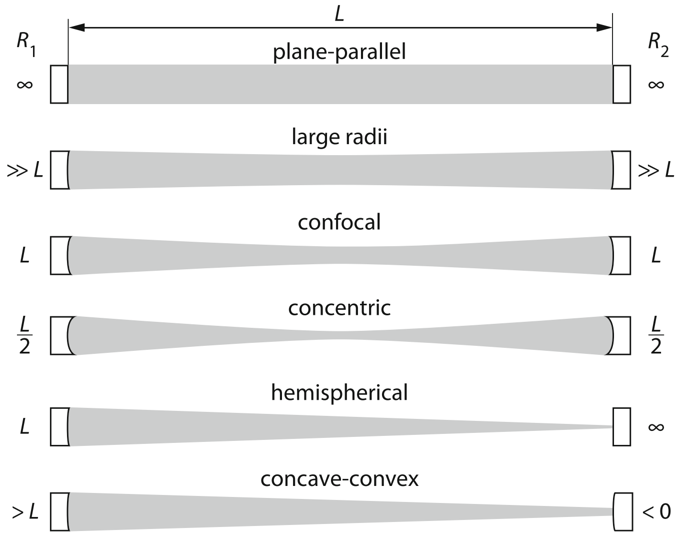

Figure 4: Types of stable resonator configurations. [1]

2.5 Transverse and longitudinal modes

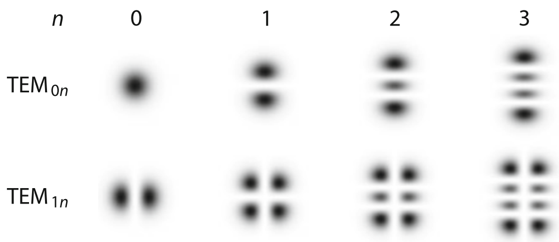

Figure 5: Select TEM_{xy} modes for rectangular geometry. [1]

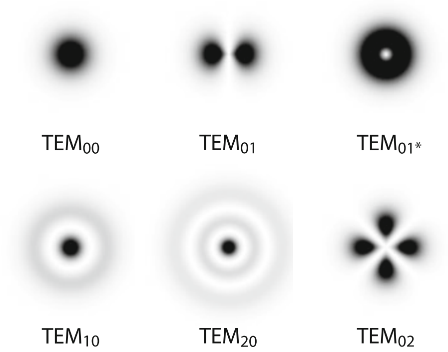

Figure 6: Select $\mathrm{TEM}_{r\vartheta}$ modes for circular geometry. [1]

2.6 Doppler broadening of the transition

Lorentzian

Gaussian

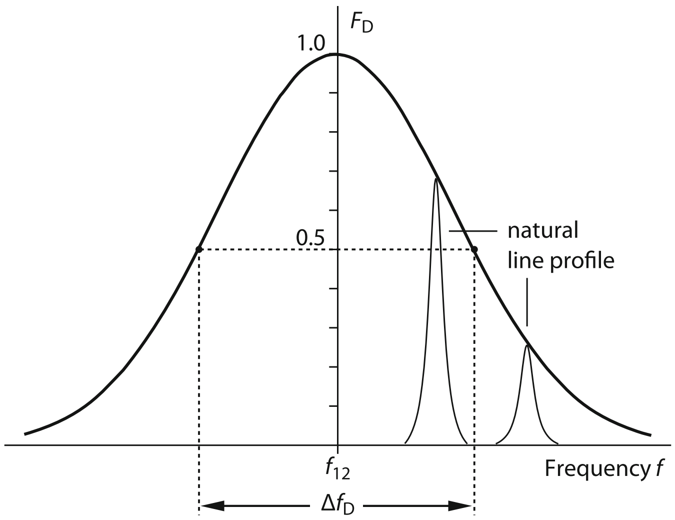

Figure 7: Typical Doppler broadening compared to natural line width. [1]

2.7 Brewster windows and polarization

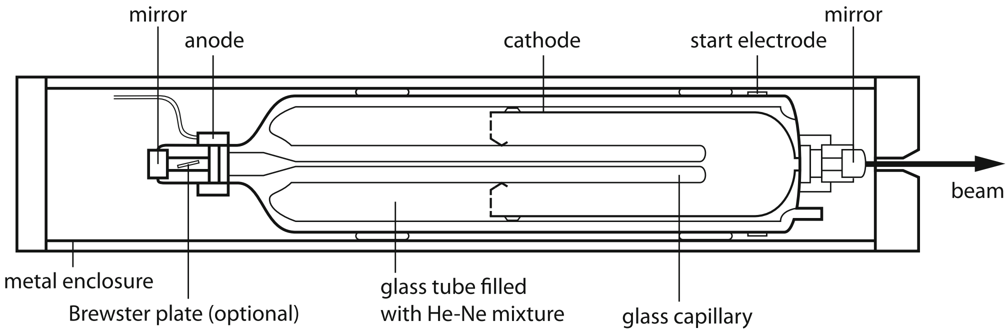

Figure 8: Schematic setup of a He-Ne laser generating polarized output. [1]

3 Procedure

3.1 Aligning the laser

3.2 Verifying the stability condition

3.3 Observing transverse modes

3.4 Determining the polarization

3.5 Analyzing spectra in multimode operation

3.6 Measuring the wavelength

4 Results

5 Discussion

References

[1] Hans Joachim Eichler, Jürgen Eichler, and Oliver Lux. *Lasers. Basics, Advances and Applications*. Springer Cham, 2018. ISBN: 978-3-319-99895-4. DOI: https://doi.org/10.1007/978-3-319-99895-4.

Appendix