Helium–Neon Laser

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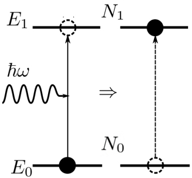
Abstract

Article studies He-Ne laser and it's basic principle of operation. Laser gain is measured. Feasibility of Malus' law is demonstrated. Mode structure of laser is examined.

Introduction and Theory

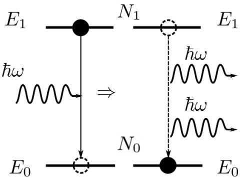
Elementary processes



a) Absorption

$$\left(\frac{dN_0}{dt}\right)_{\text{abs}} = -B_{01}N_0\rho(\omega)$$

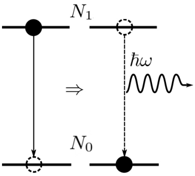
Einstein coefficients are the same $B_{01} = B_{10} = B$



b) Stimulated Emission

$$\left(\frac{dN_0}{dt}\right)_{\text{stim}} = B_{10}N_1\rho(\omega)$$

phase, direction and frequency of emitted and external photons are identical.



c) Spontaneous Emission

$$\left(\frac{dN_0}{dt}\right)_{\text{spon}} = -A_{10}N_1$$

photons radiate independently in all directions. $\frac{dN_0}{dt}$ **does not** depend on $\rho(\omega)$.

Where $\rho(\omega)$ – spectral energy density of the isotropic radiation field at the frequency of the transition.

Laser Gain

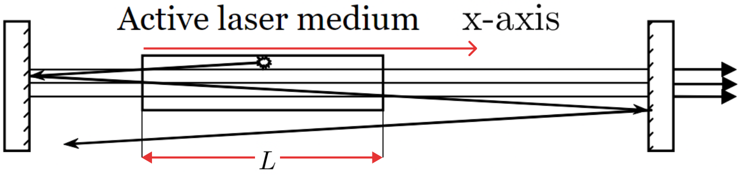


Figure: General laser scheme

Beer–Lambert–Bouguer law states that intensity of light $I(x)$ changes:

$$I(x) = I_0 \exp(\gamma x),$$

where γ – medium gain coefficient. With length L gain per period is called **laser gain**:

$$G = \exp(\gamma L).$$

Population inversion

The fact that the number of spontaneously emitted photons does not depend on $\rho(\omega)$ gives us a reason to neglect $\left(\frac{dN_0}{dt}\right)_{\text{spon}}$ term. Number of photons emitted at a time dt:

$$\frac{dN}{dt} = \left(\frac{dN_0}{dt}\right)_{\text{abs}} + \left(\frac{dN_0}{dt}\right)_{\text{stim}} = B(N_1 - N_0)\rho(\omega) \qquad (1)$$

Therefore:

$$\gamma = \frac{dI}{I} = \frac{dN \cdot \hbar\omega}{\rho(\omega)} = B\frac{\hbar\omega}{v}(N_1 - N_0), \qquad (2)$$

where $v = \frac{c}{n}$ – speed of light inside medium.

γ is positive if $N_1 > N_0$. This laser principle is called **population inversion**

He-Ne medium

Laser tube is filled with mixture of 10:1 ratio of helium and neon at pressure $P \approx 10^2$ Pa. Under this conditions, high-voltage electrical discharge is easily created. Electrical discharge is a pump source of He-Ne laser.

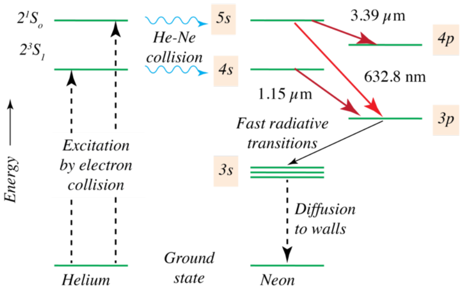
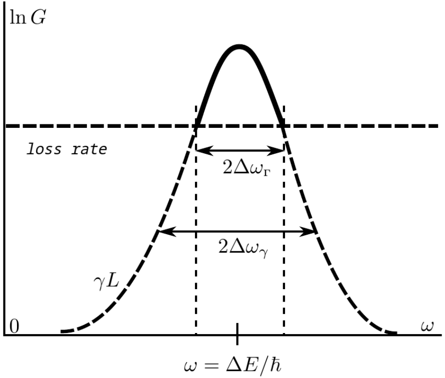


Figure: Energy levels

Electron-helium collisions excite helium atoms. In He-Ne collisions occurs very efficient transfer of excitation energy to Ne atoms. Collisions of neon with tube walls removes excitement energy of metastable 3s level.

He-Ne laser gives wavelengths in three narrow bands: at 632.8 nm, 1.15 μm and 3.39 μm.

Generation spectrum



Generation spectrum of He-Ne laser is defined by three factors: natural broadening, Doppler broadening and loss rate.

$\omega_n \approx 2\pi/\tau_n \Rightarrow \nu_n \approx 10^8$ Hz,

$\tau_n \approx 10^{-8}$ s – lifetime of 630 nm Ne transition.

$$\omega_D \approx \omega \frac{v_T}{c}, \approx 1.5 \cdot 10^9 \text{ Hz}$$

v_T – thermal motion velocity (assuming $T = 400$ K).
And loss rate reduces spectrum:

$$2\gamma L > -\ln K - \ln r_1 r_2,$$

r_1, r_2 – mirrors reflectance, K – part of remaining intensity.

Longitudinal Modes

Mode – stationary wave pattern in resonator with particular frequency and spatial distribution.

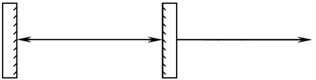


Figure: Longitudinal modes

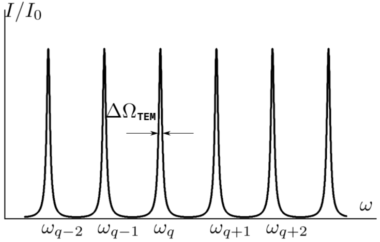
Most of the energy in resonator cavity is concentrated in standing waves. Therefore, condition on TEM_{00q} modes goes as follows:

$$L = q\frac{\lambda}{2} \Rightarrow \omega_q = q\frac{\pi c}{L} \approx 2\pi \cdot 150 \text{ MHz}, \; q \in \mathcal{N},$$

$L \approx 1$ m.

Modes spectrum

Every TEM_{00q} gives narrow spectrum $\omega_q \pm \Delta\Omega_{TEM}$.



Taking into account that

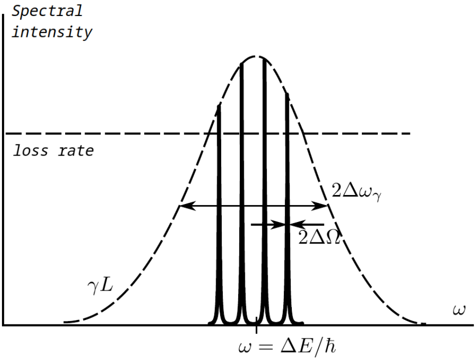
$$\Delta\Omega_{TEM} \approx \frac{\omega_q}{Q},$$

Q – Q-factor, and using common parameters of He-Ne laser we get:

$$\Omega_{TEM} \approx 2\pi \cdot 10^6 \text{ Hz}.$$

Singlemode and multimode

Applying modes spectrum to generation spectrum we get:



In generation spectrum, created by medium, resonator spectrum cuts off a few frequencies.

Estimating maximal number of longitudinal modes:

$$N_m = \omega_D/\omega_n \approx 10.$$

Transverse modes

It might seem reasonable that very large number of transverse modes would be excited. This is not true because the diffraction loss becomes very large for high transverse mode numbers. It is possible to obtain different transverse mode patterns by proper choice of mirror alignment.

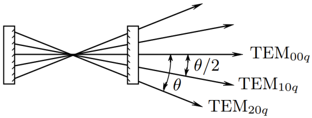


Figure: Propagation directions of modes with different transverse indices

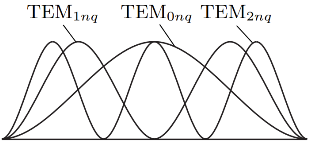


Figure: Distribution of laser radiation intensity on resonator mirror

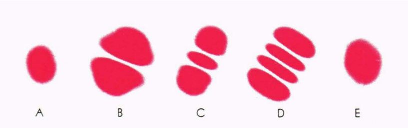


Fig. 2—Transverse electromagnetic mode patterns: (A) TEM_{00q}; (B) TEM_{01q}; (C) TEM_{02q}; (D) TEM_{03q}; and (E) TEM_{01q}^{*}.

Theory of such distribution is complicated. [a]

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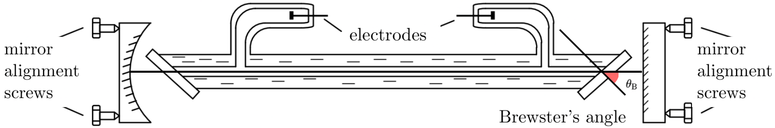
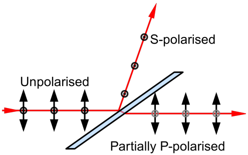
[a] "Laser modes", B. F. Hochheimer and J. T. Massey.

Polarization of Laser Emission





To remove reflections from laser's windows the Brewster's angle properties can be used:

$$r_p = \frac{E_r}{E_i} = \left. \frac{n_2 \cos\theta_i - n_1 \cos\theta_t}{n_2 \cos\theta_i + n_1 \cos\theta_t} \right|_{\theta_i = \theta_B} = 0$$

Malus' law

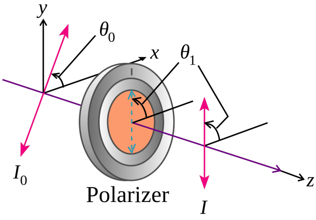


Figure: Malus' law (here $\theta_i = \theta_1 - \theta_0$)

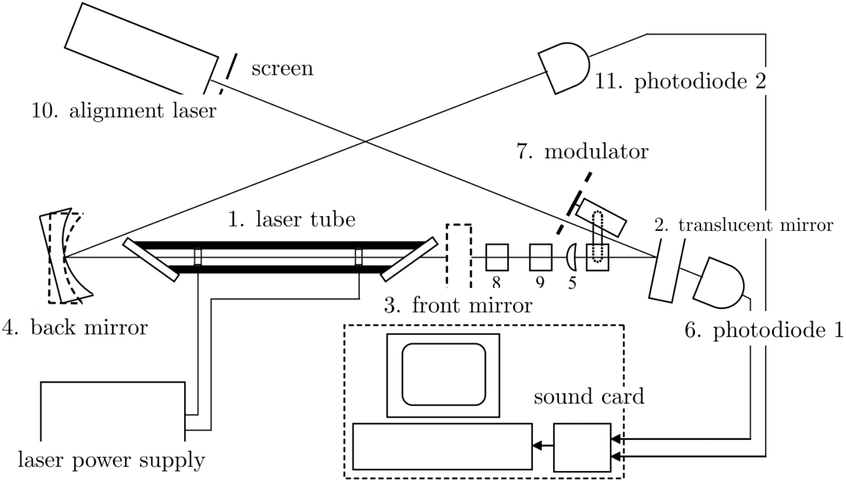
To study the laser's polarization, polaroid and Malus' law is used:

$$I(\theta_i) = I_0 \cos^2 \theta_i, \tag{3}$$

where I_0 is the initial intensity and θ_i is the angle between the light's initial polarization direction and the axis of the polarizer.

Measurements and Results

Experimental setup



Experimental Setup

Figure: Photo of laboratory setup

Adjustment

Figure: Image of laser beam after laser tube

Laser gain is measured with additional laser and a pair of photodiodes. We need laser beam to pass through laser tube without dissipation on tube walls.

To achieve laser generation we need fine adjustment of front and back mirrors of laser. Additional laser is used for that purpose. We adjust back mirror until reflection of alignment laser appears over it's output window. The same procedure applies to the front mirror.

Laser Gain

Laser gain is measured using two photodiodes, connected to sound card. To exclude the influence of photodiodes dark current and ambient illumination we use modulator. Therefore, we can measure AC. Intensities are measured with and without amplification (I_i^{on} and I_i^{off}).

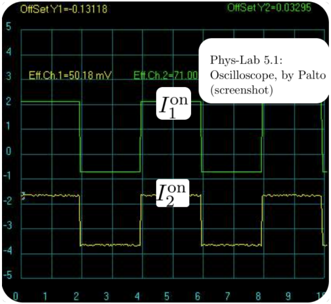


Figure: Phys-Lab 5.1: Oscilloscope, by Palto (screenshot)

Photodiodes are connected to the sound card with the ADC. This gives us a direct way to measure intensity.

$$G = \left(\frac{I_1^{\text{on}}}{I_1^{\text{off}}} \right) / \left(\frac{I_2^{\text{on}}}{I_2^{\text{off}}} \right),$$

where I_i^j – r.m.s. light intensity. Series of measurments gives the following result:

$$G = 1.029 \pm 0.006$$

Laser Polarization

When laser generation is active we can measure polarization. Polarization is measured using single photodiode and normalized.

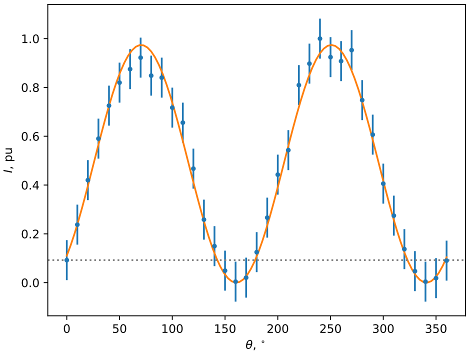


Figure: Intensity for different polaroid angles

Interpolating according to (3):

$$I(\theta) = A\cos^2(\Omega\theta + \theta_0),$$

We obtain the following parameters' values:

$$\Omega = 0.998 \pm 0.005$$

$$\theta_0 = (-70 \pm 1)^\circ$$

This demonstrates that Malus' law holds with a great precision.

Transverse modes

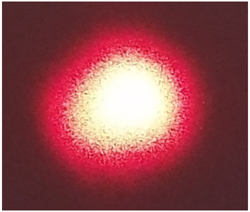


Figure: TEM_{00q}

Figure: TEM_{01q}

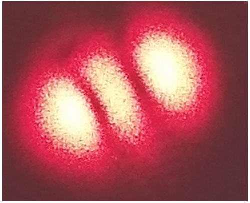


Figure: TEM_{02q}

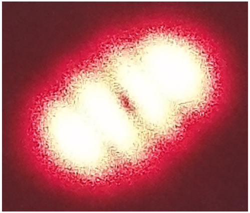


Figure: TEM_{03q}

Non-trivial transverse modes

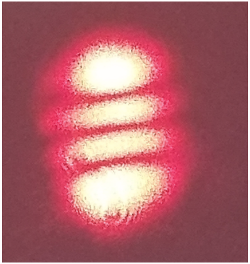


Figure: TEM_{30q}

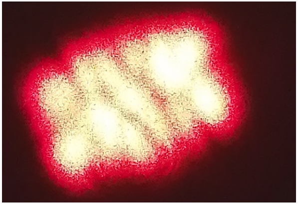


Figure: Large number of modes

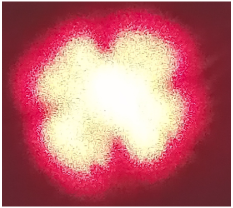


Figure: $TEM - "clover"$

Figure: TEM

Conclusion

Laser generation was achieved. Laser gain evaluated to:

$$G = 1.029 \pm 0.006.$$

Malus' law was demonstrated to hold (3):

$$\Omega = 0.998 \pm 0.005$$

$$\theta_0 = (-70 \pm 1)^\circ$$

Thank you for your attention!