TOMSK POLYTECHNIC UNIVERSITY

F.A. Gubarev

Basics of Laser Safety. A Study of the Operation Principle and the Parameters of the Emission of a Helium-Neon Laser

Laboratory Guide
to the Lab Work No 3

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The aim of the work:

To get acquainted with the principle of action and design of a helium-neon laser. To study safety techniques when working with laser radiation.

Preleminary task

1. Familiarize yourself with the main types of instruments for measuring the power of radiation.
2. To study the principle of action and the method of creating an inversion in a helium-neon laser.
3. Calculate the quantum efficiency of the He-Ne laser for the main lines of generation ($\lambda1$ = 632.8 nm, $\lambda2$ = 1.15 μm, $\lambda3$ = 3.39 μm).

Safety instructions for working with lasers

Laser radiation (direct, reflected or scattered) upon ingression into the eyes and onto the skin of a person can cause damage to them. Absorbed by biological tissues, laser radiation can lead to irreversible processes in the living body. In particular, the energy of laser radiation can turn into thermal energy, causing skin burns, or coagulation of blood vessels. Under the influence of powerful radiation, hair can become discolored and the skin can be destroyed.

The effect of laser radiation on biological objects depends on the power of the light flux, the wavelength of radiation, and the mode of operation of the laser. Low-power continuous-action lasers have mainly a thermal effect, which leads to photocoagulation. More powerful laser systems (in particular CO2, CO - lasers are capable of cutting tissue, which is used in laser surgery). Impulse lasers with a pulse duration of from ns to ms and pulse energy from one to thousands of J, in addition to thermal action, can lead to explosive processes in the tissues.

Experiments on animals have unequivocally established that laser radiation affects the nervous system. Thus, when the brain of the mice was irradiated with a focused laser beam, paralysis developed, and death occurred. Especially dangerous is laser radiation for the eyes, even the smallest helium-neon and semiconductor lasers. The allowable power and energy densities (for the case of impulse action) for the organs of vision are established by experimental methods on animals: for continuous radiation, 0.35 W / cm2, for pulses with a duration of about 30 microseconds, 0.27 J / cm2.

Simple estimates show that the emission of a low-power helium-neon laser upon entry into the eye can disrupt the retina. We carry out this estimate. Let the laser power be 1 mW. The optical system of the eye is akin to a collective (focusing) lens. Therefore, the power density p of the laser radiation at the focus of the lens is:

$$p = (D / F\lambda)^2 P,$$

where P is the power of the laser, D is the diameter of the lens (in this case, the entrance pupil), F is the focal length of the system (for the eye F = 1.5 cm), λ is the radiation wavelength, λ = 632.8 nm. *D* varies depending on the brightness of irradiation from 1 to 7 mm. Assuming for simplicity that *D* = 0.1 cm, we have:

P = (0.1 cm / 1.5 cm · 0.00006 cm) ^{2} · 0.001 W = 1.2·103 W/cm^2,

this significantly exceeds the allowable value (0.35 W/cm^2). It is obvious, that the diameter of the pupil, which varies with the illumination, is of great importance. Therefore, it is recommended to work with lasers in well-lit rooms, when the diameter of the pupil is minimal. However, it is difficult to satisfy this requirement when setting up works - they are held in a darkened room.

Thus, a direct hit in the eye of radiation from a low-power laser, or from reflected or scattered radiation from a powerful laser, is dangerous for staff and patients. At high powers and energies, as noted above, the skin and hair cover, the central nervous system, can suffer.

Accordingly, a list of protective measures is needed:

1. First of all, this definition of the maximum permissible levels of power (for continuous and quasi-continuous) lasers and energies (for impulse) for the eyes, skin, normal functioning of the nervous system, etc.

2. Development of rules for labor protection in rooms where laser installations operate (requirements for premises).

3. Development of rules for the operation of laser installations (in particular, to the used ones).

If the eye is damaged by laser radiation, it is necessary to bandage the injured eye and immediately send the victim to the medical doctor.

Principle of operation of helium-neon laser

Helium-neon laser is a typical representative of gas lasers. When the active medium is pumped, the principle of resonance transfer of excitation energy from the impurity gas of helium to the ground-neon is used. Generation occurs on atomic transitions of neon atoms. The laser emits at several wavelengths, the most notable of which is $\lambda = 632.8$ nm (red). Among the other lines there are two lines in the infrared range with $\lambda = 1.15$ and 3.39 μm, and also green at $\lambda = 543$ nm. A helium-neon laser, generating at the transition with a wavelength $\lambda = 1.15$ μm, was the very first gas laser, moreover, it demonstrated for the first time a continuous laser generation.

A simplified diagram of the energy levels of an He-Ne laser is shown in Fig. 1. It is evident from the diagram that in the He atom the 23S1 (excitation energy 19.81 eV) and 21S0 (20.61 eV) levels are close to resonance with the 2s2 (19.78 eV) and 3s2 (20.66 eV) states of the atom Ne. Since the 23S1 and 21S0 levels are metastable, the He atoms in these states are very effective for the excitation of the 2s and 3s levels of Ne atoms by resonant energy transfer. The transfer of energy from helium atoms to neon atoms is carried out in inelastic collisions of the second kind, i.e. Such that the internal energy from one colliding particle is transmitted by another. The energy difference between the corresponding levels is compensated for by the thermal energy of the colliding atoms, which amounts to $kT = 0.026$ eV at room temperature ($T = 300$ K). It was established that in this He-Ne laser this excitation mechanism is dominant in obtaining population inversion, although pumping, in addition, can also be realized due to collisions of electrons with Ne atoms. Since the 2s and 3s levels of the Ne atom can be sufficiently populated, they are well suited to the role of the upper levels of laser transitions. Transitions to p-states are possible as possible laser transitions. Moreover, it should be noted that the relaxation time of the s-states ($\tau s = 100$ ns) is an order of magnitude greater than the relaxation time of the p-states ($\tau p = 10$ ns), so that the condition of continuous generation is met. It should also be noted that the probability of excitation from the ground state to the 2p and 3p levels (due to the electron impact), because of the smaller cross sections of the interaction, is significantly less than the corresponding excitation probabilities to the 2s and 3s levels. However, direct excitation to the 2p and 3p levels also has a significant effect on laser performance.

It follows from the above that generation in neon can be expected to occur between 3s or 2s levels (playing the role of upper laser levels) and 2p or 3p levels, which can be considered as lower laser levels. For junctions with widely differing wavelengths ($\Delta\lambda > 0.2\lambda$), each specific junction on which the lasing is generated is determined by the wavelength at which the maximum of the reflection coefficient of the multilayer dielectric mirror (resonator) is "tuned" . Laser transitions are broadened primarily due to the Doppler effect. For example, for a red He-Ne transition ($\lambda = 633$ nm in vacuum and $\lambda = 632.8$ nm in air), Doppler broadening leads to the width of this line being of the order of ~ 1.5 GHz. For comparison, we can estimate the value of the intrinsic broadening:

$\Delta\nu_{nat} = 1/2\pi\tau = 19$ MHz, where $\tau^{-1} = \tau_s^{-1} + \tau_p^{-1}$.

The broadening associated with the collision processes is even less than the intrinsic broadening (for example, for pure Ne we have ΔvC = 0.6 MHz at a pressure p = 0.5 mm Hg). Excitation of the gaseous medium is usually carried out by a stationary low-current glow discharge. The discharge current density is 100-200 mA / cm2. In collisions of helium atoms (in the ground state) with electrons of a glow discharge plasma, excited helium atoms are created:

e + He → He * + e ± ΔE, (1.1)

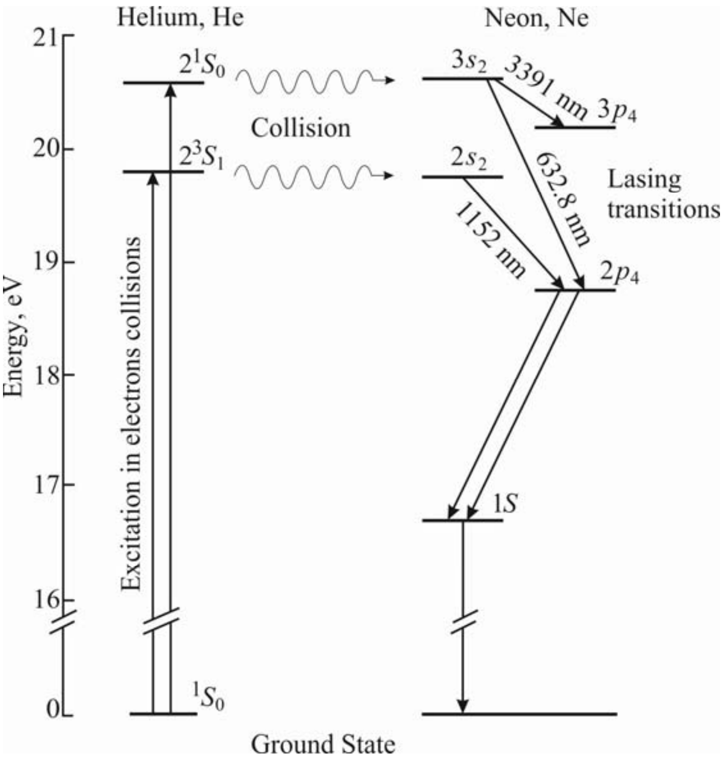

Fig. 1. Energy levels diagram of He-Ne laser

Here an asterisk indicates an excited helium atom, and ΔE is the energy lost by a "fast" plasma electron in a collision (about 20 eV, in our case). The processes occurring according to the scheme (1.1) are usually called collisions of the first kind; Such that the kinetic energy of one particle (in this case an electron) is transferred to the internal energy of the other (the helium atom).

Some of the excited atoms produced in the reaction (1.1) in non-elastic collisions with helium atoms in the ground state and electrons are in the 23S1 and 21S0 states. Since the 23S1 and 21S0 states are long-lived compared to the radiating states, the main mass of the excited helium atoms in the discharge are precisely these atoms. Inelastic collisions of the second kind according to scheme

He (2^3S_1) + Ne → He + Ne* ($2s_2$) ± kΔT

He (2^1S_0) + Ne → He + Ne* ($3s_2$) ± kΔT (1.2)

Pumping of the upper working states of the neon is carried out.

Direct excitation of the neon levels from the ground state by "fast" electrons by collisions of the first kind is undesirable, since the lower operating states $2p_4$ and $3p_4$ will also be populated, which will lead to a breakdown of the inversion. To avoid this, the concentration of neon atoms is taken by an order of magnitude less than the concentration of helium atoms.

Thus, the use of a helium buffer gas allows selective pumping of $2s_2$ and $3s_2$ states of neon. The lifetime of the atoms in these states is, as noted above, an order of magnitude greater than the lifetime in the $2p_4$ and $3p_4$ states, so between pairs $3s_2$ - $2p_4$ (radiation wavelength 632.8 nm), $2s_2$ - $2p_4$ (1152 nm), $3s_2$ - $3p_4$ (3391 nm), an inversion is formed and induced emission occurs. Levels of $2p_4$ and $3p_4$ neon spontaneously break down (cleaned) to a block of metastable levels 1s. The latter leave the discharge due to diffusion to the wall. Naturally, this process is more efficient in narrow discharge tubes, so the working diameters of the tubes are a few millimeters. The length of the tubes is several tens of centimeters, up to 1-2 m, because the gain is small. Typical parameters of helium-neon lasers are given in Table. 1.

The gas pressure	about 1 mm Hg
The ratio of the partial pressures of helium and neon	about 10/1
Diameter of the tube	2–8 mm
length of the tube	20–200 cm
discharge voltage	1–4 kV
Discharge current	10–50 mA
Radiation wavelengths	0.63; 1.15; 3.39 μm
Power of radiation	Units to hundreds of mW
Line bandwidth	1.5; 2.7; 8.0 GHz
Divergence of radiation	0.5–1 mrad
Power consumption	of tens to hundreds of watts
Lifetime	thousands of hours

The optimal diameter is due to the competition between the two factors. On the one hand, when the cross section of the active medium of the laser increases, other things being equal, the output power increases. On the other hand, a decrease in the diameter of the capillary of the gas-discharge tube increases the amplification factor in proportion to 1 / D. The latter occurs both because of the increase in the probability of decay on the capillary wall of the metastable state of neon 1s, and also because of the increase in the amount of excited helium (and thus neon), and hence, the gain coefficient for co- Storing the product p · D constant, that is, When the condition of similarity of glow discharges is satisfied when the diameter of the gas-discharge tube is changed.

The presence of the optimum discharge current density is due to the occurrence of step-like processes of the type

E + Ne (1s) → Ne (2p) + e, (1.3)

leading to a decrease in inversion. In addition, at high current densities, deactivation of the metastable states (2^3S_1 and 2^1S_0) of the He atom occurs not only due to collisions with the walls, but also for superelastic collisions of the type (considers, for example, the 2^1S_0 level):

He (21S0) + e → He (1S0) + e. (1.4)

Since the rate of this process is proportional to the electron density Ne, and hence to the current density J, the total deactivation rate can be written as $k_2 + k_3J$. In this expression, k_2 is a constant characterizing the deactivation due to collisions with the walls, and k_3J (where k_3 is also a constant) is the rate of processes associated with superelastic collisions (1.4). On the other hand, the excitation speed can be written as k_1J, where k_1 is also a constant. Under the steady-state conditions, $N_0k_1J = (k_2 + k_3J) N^*$, where N_0 is the population of the ground state of the He atom, and N* is the population of the excited state 2^1S_0. The equilibrium value of the population of the 2^1S_0 level is given by the expression:

$$N^* = N_0 \frac{k_1 J}{k_2 + k_3 J}, \quad (1.5)$$

From which it can be seen that at a high current density there is a saturation of the population. Since the equilibrium population $3s_2$ of the state of the Ne atom is determined by the resonant energy transfer from the 2^1S_0 state of He, the population of the upper laser level $3s_2$ will also become saturated with increasing current density J. On the other hand, it was found experimentally that in the absence Generation, the population of the lower laser level ($2p_4$ or $3p_4$) continues to grow linearly with increasing J (Fig. 2) due to direct pumping of Ne atoms from the ground state and cascade radiative transitions from the upper laser levels. Thus, as the discharge current density increases, the population difference, and with it the output power, increases to some optimal value, and then decreases.

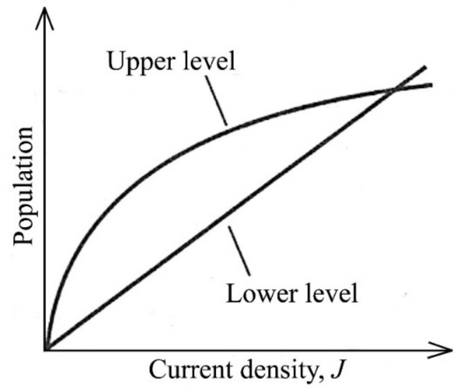

Fig. Schematic dependences of the populations of the upper and lower levels of the He-Ne laser on the discharge current density

Helium-neon lasers, as a rule, have a block design and consist of a power supply and a direct radiator in which there is a glass gas-discharge tube (GRT) located in a resonator formed by one "deaf" and one partially transmissive mirror. Mirrors have a dielectric multi-layer coating with a maximum of reflection at one (or several) wavelengths. Radii of curvature of mirrors are chosen so that at a given distance between mirrors a stable optical resonator is formed. Mirrors of the resonator are fixed in special heads, the mechanism of which allows to adjust the resonator with the necessary accuracy. The heads can be located on a common rigid base or can be joined to the frame of the laser housing. In the latest designs, so-called "internal" mirrors are used, which simultaneously serve as exit windows for the discharge tube. Such designs do not require additional tuning of the resonator (alignment).

To reduce losses in the emission of radiation, the ends of the GRT are located at the Brewster angle to the optical axis of the resonator. In the case of internal mirrors, the Brewster window is placed directly inside the GRT. For what purpose are Brewster windows used? As is known, the reflection coefficient from the surface separating two media with different refractive indices depends on the angle of incidence, the relative refractive index and the type of polarization of the incident radiation. Under normal incidence, the losses will vary between 7 and 13%, and considerably exceed the amplification in the active medium of a He-Ne laser at a wavelength of 0.63 μm; consequently, the self-excitation condition is not satisfied and laser generation is impossible.

With oblique incidence of radiation, the reflection coefficient essentially depends on the orientation of its polarization plane. In the case of coincidence of the plane of polarization of the incident radiation with the plane of incidence, when the angle of incidence is equal to the Brewster angle, the reflection coefficient becomes zero. To determine the Brewster angle, we can use the simple relation: $tg\alpha_{Br} = n$ where n is the relative refractive index. In particular, for the glass-air interface, n = 1.5-1.6 and α_{Br} = 56-58 °. It is at such an angle to the optical axis of the tube that the end plate must be placed to reduce the loss of reflection to a minimum. In this case, the radiation at the output becomes linearly polarized.

Typical values of the radiation power of helium-neon lasers are tens of milliwatts in the regions of 0.63 and 1.15 μm and hundreds in the region of 3.39 μm. The service life of lasers, in the absence of errors in manufacturing, is limited to processes in the discharge and is calculated for years. Usually the manufacturer guarantees a minimum operating time of ~ 10,000 hours. With the passage of time, a disruption occurs in the discharge of the gas composition. Due to the sorption of atoms in the walls and electrodes, a process of "tightening" occurs, pressure drops, and the ratio of the partial pressures of He and Ne changes. Therefore, the radiation power gradually decreases.

The efficiency of the He-Ne laser at all laser transitions is very low ($<10^{-3}$). The main reason for such a low efficiency is the small magnitude of the quantum efficiency of the laser. Indeed, each elementary pumping process requires an energy expenditure of about 20 eV, while the energy of the laser photon does not exceed 2 eV. On the other hand, the presence of a very narrow amplification line in such a laser is an obvious advantage in obtaining lasing in a single-mode regime. If the length of the resonator is sufficiently small (<15-20 cm), generation in one longitudinal mode can be realized by fine tuning of the resonator length (for example, using a piezoceramic device), thus achieving a coincidence of the mode frequency With the center of the gain loop. In a single-mode He-Ne laser, it is possible to provide a very high degree of stabilization of the frequency $\Delta\nu/\nu = 10^{-11} - 10^{-12}$.

Generating on the red He-Ne transition, lasers are still widely used in many areas where low-power coherent radiation of the visible range is required (for example, for adjusting devices or when reading barcodes). In supermarkets, red He-Ne lasers are used to read the in-formation contained in the barcode of each product. However, the main competition for He-Ne lasers is provided by semiconductor lasers emitting in the red range, which turn out to be more compact and more efficient. Nevertheless, He-Ne lasers in the green range, due to the fact that the green light is much better perceived by the eye, is increasingly being used when adjusting the instruments, and also in the cellular cytometry. In addition, single-frequency He-Ne lasers are often used in metrological applications (for example, in high-precision interferometric devices for measuring distances) and in holography. In medicine, He-Ne lasers are used for low-intensity laser therapy.

The main manufacturer of He-Ne lasers in Russia is R&D Enterprise "Plasma", Ryazan. At present, He-Ne lasers emitting at a wavelength of 0.63 μm are commercially available with an average lasing power of 0.5 to 8 mW with a typical radiation divergence of 1.2-4.3 mrad. To perform this laboratory work, it is proposed to use a laser with a radiation power of 3 mW with a common industrial power source. The use of modern elemental base allowed to significantly reduce the mass and dimensions of the device, mainly the power source, in comparison with LH 56. GN-3-1 has a separate power unit with dimensions 150x60x170 mm and weighing 1.2 kg. Since the power of the laser radiation is low, photodetectors, both thermal action and photodiode based, can be used for its measurement.

In-lab task

1. To familiarize yourself with the principle of operation and functional designation of the IMO-2 and Ophir PD-300 radiation power meters with a display.
2. To study the design, principle and operating conditions of a helium-neon laser (for example, the lasers GN-3-1 and GN-5-1).
3. Visually determine the wavelength of the radiation.
4. Measure the output power of the laser radiation (using the IMO-2 and Ophir PD-300 receivers).
5. Estimate the full efficiency of the laser, if the power consumption of the network is 15 W.
6. Express your thoughts on the degree of danger of working with laser radiation.

7. Using a collecting lens, measure the power of the incandescent lamp (measurements are made using IMO-2).
8. Explain the difference between lasers and sources of spontaneous emission.

Control Questions

1. Explain the conditions for the existence of continuous generation.
2. What is the efficiency of the He-Ne laser, and by what factors is it determined?
3. At what wavelength, 0.63 or 3.39 μm laser efficiency is higher?
4. What is the wavelength of the radiation and how is it caused?
5. How is the upper working level pumped?
6. How is the lower working level extinguished?
7. What determines the diameter of the gas-discharge tube of a laser? What will happen if you make a diameter larger / smaller?
8. What is the length of the GRT? What happens if you make it bigger / smaller?
9. Is the ratio of the partial pressures of gases in the working medium of a laser?
10. What wavelengths can be obtained from an He-Ne laser?
11. What type of discharge is used in a He-Ne laser? What are its electrical parameters?
12. What is the reason for the restriction on the discharge current density?
13. What structural elements does the modern He-Ne laser contain?
14. At what wavelength, 0.63, 1.15, or 3.39 μm is higher than the laser gain?
15. Write down the condition for the existence of standing waves.
16. What are the main precautions to avoid injuries by laser radiation?