Theoretical background to lasers.

LASER (abbreviated from Light Amplification by Stimulated Emission of Radiation) is a source of a coherent electromagnetic radiation. Such a radiation is generated in a process of a stimulated emission. Laser's operation is correlated with three physical processes: absorption (Fig. 1a), spontaneous emission (Fig 1b) and finally stimulated emission (Fig. 1c).

Let's consider a molecule having two levels of energy: W_1 and W_2. The level W_1 is the ground state, whereas the level W_2 corresponds to the excited state. The energy of W_2 is higher than the energy of W_1. Therefore, the transition from W_1 to W_2 is accompanied by the absorption of radiation, whereas the transition from W_2 to W_1 is accompanied by the emission of radiation. According to the Planck's theory, the energy of absorbed or emitted radiation is equal to $h\nu_{12} = W_2 - W_1$, where: h – Planck's constant, ν_{12} – frequency of the radiation. In room temperature a great majority are molecules in the ground state W_1. If molecules absorb radiation with energy equal to $h\nu_{12}$ they go to the excited state W_2 (Fig 1a). The excited state is, however, very unstable – it means that molecules spend very short time in the excited state. After this time molecules spontaneously emit radiation with energy equal to $h\nu_{12}$ and go back to the ground state. This is a spontaneous emission of radiation (Fig 1b).

The process of emission of radiation can also be stimulated. A stimulated emission occurs when molecules, which are already in the excited state, are irradiated with radiation having energy equal to $h\nu_{12}$ (Fig 1c). In such a case excited molecules emit stimulated radiation with energy equal to $h\nu_{12}$ and go back to the ground state. Because of the stimulated emission the intensity of the stimulating radiation is increased. Importantly, the stimulated radiation is coherent with the stimulating radiation. Since usually only a small number of molecules exist in the excited state, the probability of stimulated emission (P_B) is much lower than the probability of spontaneous emission (P_A). The ratio of these probabilities can be described applying the Einstein's formula:

$$P_A / P_B = \exp\{h\nu/kT\} - 1 \qquad (1)$$

Where: k – Boltzmann's constant, T – absolute temperature (in Kelvins). From this formula we can conclude that if $h\nu \ll kT$ the term (P_A / P_B) is almost zero (stimulated emission predominates), whereas if $h\nu \gg kT$ the term (P_A / P_B) is almost infinite (spontaneous emission predominates). If $h\nu$ and kT are comparable to each other, both types of emission are present.

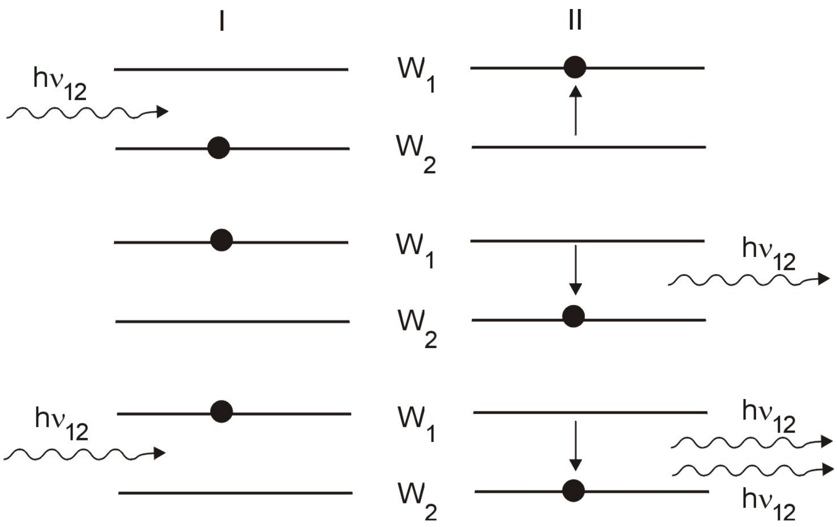

Figure 1. Transitions of a molecule from the initial state (I) to the final state (II) in case of absorption of radiation (a), spontaneous emission of radiation (b) and stimulated emission of radiation (c). The black dot symbolizes the energetic state of atom. Further description in text.

In order to stimulate the laser action we must obtain so called „population inversion". This situation occurs when the number of atoms in the excited state is higher than the number of atoms in the ground state. How to obtain this ?

Let's assume that we have a system with two energy states with energies equal to E1 (ground state) and E2 (excited state), respectively. When the system is in the thermodynamic equilibrium, the number of molecules in the states E1 and E2 is determined by the Maxwell-Boltzmann's statistics. Let's assume that the number of molecules in the state E1 equals N1 and the number of molecules in the state E2 equals N2. According to the Maxwell-Boltzmann's statistics: N1 is much higher than N2.

Let's irradiate our system with electromagnetic radiation having the energy equal to: $h\nu_{12} = E2 - E1$. Some atoms in the state E1 will absorb the radiation's energy and undergo a transition to the state E2. Other atoms in the state E2 will emit the stimulated radiation and undergo the transition to the state E1. If we increase the radiation's intensity, both the absorption and the stimulated emission will be increased. Finally the number of molecules in both states will be equal, thus N1=N2. This is not yet the population inversion, but only the population equilibration. In case of the population inversion: N2 > N1.

To obtain such an inversion we must have a system with at least three energy states: one ground state with energy E1 and at least two excited states: at least one state with an increased stability (so called „metastable" state) having energy equal to E2, and at least one „normal" excited state having low stability and the energy equal to E3. The energy E3 is higher than the energy of E2 and the energy of E2 is higher than the energy of E1, thus E3 > E2 > E1. The number of molecules in the states E1, E2 and E3 equals to N1, N2 and N3, respectively.

In order to obtain the population inversion we must irradiate the system with electromagnetic radiation having the energy equal to: $h\nu_{13} = E3 - E1$. This is so called „optical pumping" (Figure 2). This process leads to equilibration between the states E3 and E1, thus N3 = N1. Some molecules, which are in the state E3 undergo a transition to the state E2 (Figure 2). Since E2 < E3, this is a spontaneous process. Because the state E2 is more stable than E3 (it means that an average molecule spends much more time in E2 than in E3), the number of molecules in the state E2 will be higher than the nuber of molecules in the state E3, thus N2 > N3. Since N2 > N3 and N3 = N1 (see above), thus N2 > N1. Now, there is a population inversion and the system is ready for the laser action. In order to stimulate the laser action one should irradiate the system with electromagnetic radiation having the energy equal to: $h\nu_{12} = E2 - E1$. Since there is a population inversion, a stimulated emission of laser radiation having the frequency equal to ν_{12} occurs from the state E2 to E1 (Figure 2).

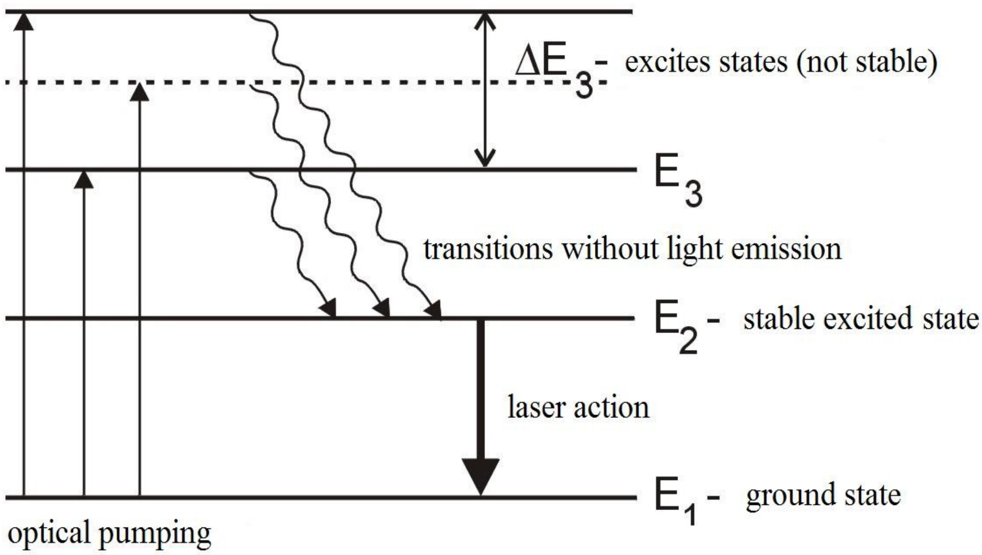

Figure 2. Scheme of energy levels in molecules and the mechanism of the laser's action.

The laser used in our laboratory is the semiconductor laser made of galium arsenate (GaAs) dopped with zinc or cadmium atoms. Electric contact is provided by thin layers of silver, which are spread on the surfaces of the semiconductor layer. The laser dimensions are: 0.1 mm x 0.3 mm x 1 mm. The emitted laser light has the wavelength equal to 650 nm, which corresponds to the red light. The most important parameters, which characterize semiconductor lasers are:

a) relationship between the surface density of the laser radiation's power (the power per unit of the surface area) and the density of the current (current's intensity per unit of surface area) passing through the laser diode (Figure 3).

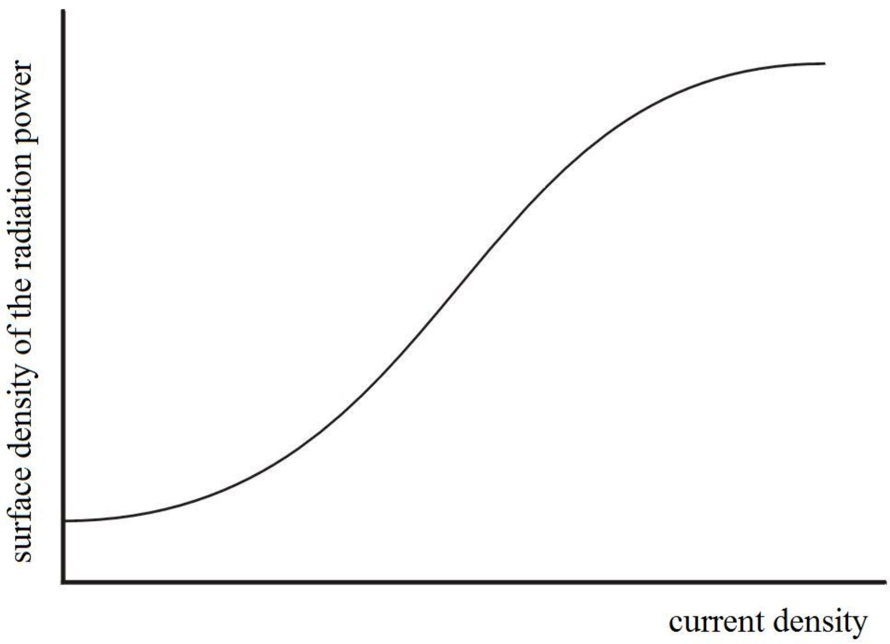

Figure 3. The surface density of the laser radiation's power as a function of the density of the current passing through the laser diode.

The depicted function plots the relationship at a given temperature (in this case 4.2 K for the GaAs laser). In the point, in which the slope of the curve reaches its maximal value the current's density reaches the threshold value of 10^3 A/cm^2 and the radiation power's rise with the current density is the highest. Such a point defines the current density threshold – the value of the current's density necessary to evoke the laser's action. When the temperature rises the curve depicted in Figure 3 is shifted to the right but its shape remains unchanged.

b) relationship between the current density threshold and temperature.

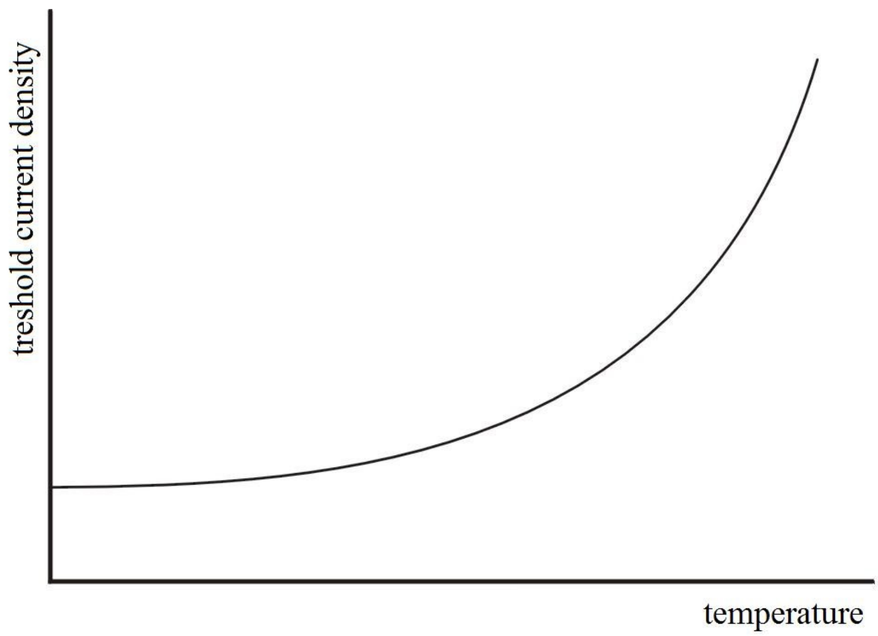

Figure 4. The current density threshold as a function of temperature.

As we can see the current density threshold rises strongly with rise of temperature. At room temperature the value of the current density threshold is about 10^5 A/cm^2.

One of the most important properties of a laser is a high efficiency of conversion of electric energy into light energy. This is so called „external efficiency" defined as a ratio of number of emitted light photons to number of electric charges injected into the laser's semiconductor. The value of this efficiency may reach 70% for the GaAs laser.

c) relationship between the intensity of emitted radiation and the wavelength at different current densities (Figure 5)

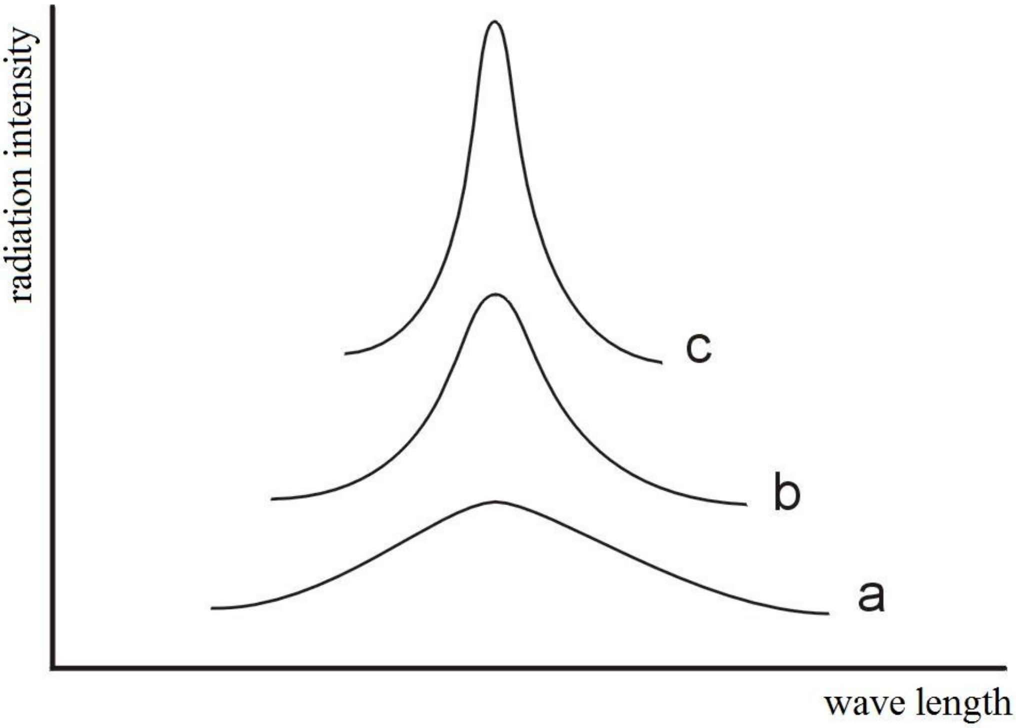

Figure 5, Intensity of emitted radiation as a function of the wavelength at different current densities, a – the current density lower than the threshold value, b and c – increasing current densities higher than the threshold value.

It can be seen that rising of the current density increases the intensity of emitted radiation especially at the wavelength, which corresponds to the maximum of radiation intensity.

The radiation emitted by lasers is characterized by:

- coherence - the emitted waves are ordered in space, phase and time
- monochromatism – the emitted waves have the same well-defined wavelength
- parallelism – the laser light beam has one well-defined direction and can be easily focused by optical systems
- high surface density of the power (from 10^6 to 10^8 W/cm^2)

Application of lasers in medicine and stomatology

Since the laser light is coherent and monochromatic, it can be generated in a form of very narrow beams. Because of this, the energy of the laser beam can be focused on a very small area. This increases the surface density of the power of the beam.

Laser beam interacts with cells and tissues in body. These interactions lead to phenomena such as reflection, dispersion, transmission and partial or total absorption of the beam. The most important are the processes of the absorption. Theses processes cause photobiochemical, photothermic and photoionisation effects in tissues. The presence of such effects depends on the magnitude of the surface density of the beam power and its energy per unit of surface area.

Results of research provide evidence that laser light with the wavelength from 600 to 900 nm and the surface densities of the power not higher than 50 mW/cm^2 can exert following photochemical effects:

- increase of the electrolyte exchange rate between cells and their environment
- antimutagenic activity
- acceleration of mitosis
- changes in structure of biological membranes
- increase of activity of enzymes
- increase of rate of ATP and DNA synthesis

The phenomena listed above lead, on the level of a whole cell, to desired biostimulatory effects, such as:

- improvement of blood circulation in capillaries
- stimulation of angiogenesis
- immunomodulation
- increase of amplitudes of action potentials in nerve cells
- rising of concentration of hormones
- hypocoagulation

The best results in the area of photobiostimulation can be achieved using He-Ne lasers, semiconductor lasers and dye lasers.

The photothermic effects caused by laser beam are:

- photohyperthermia – rise of temperature of tissue, which may damage the tissue structure and cause a partial denaturation of enzymes,
- photocoagulation – denaturation of enzymatic proteins and DNA
- photocarbonisation – carbonisation of cells and tissues

These effects require higher surface densities of of the beam power (from 1 to 10^6 W/cm^2) than photobiochemical effects and they need a time between milliseconds and seconds to occur.

The photoionisation effects of lasers can be:

- photoablation – foliation of tissues
- photofragmentation
- photodisruption of tissues

The photoionisation effects require even higher surface densities of of the beam power (from 10^6 to 10^{12} W/cm^2) and shorter times (from picoseconds to nanoseconds) than photobiochemical effects.

The development of laser technology enhanced the area of lasers' application both in medicine and in stomatology, both for diagnostic and therapeutic purposes. One should mention the still raising lasers' application in experimental techniques in biomedicine. Lasers are also applied widely in surgery.

The advantages of lasers in relation to traditional methods are:

- possibility of interactions with diseased areas only and omitting healthy tissues (if diseased areas have different absorption properties)
- use of laser beam as a „laser knife" for operations without mechanical contact with tissues
- shortening of time of operation and diminishing of bleeding of tissues
- possibility of operating infected tissues
- decrease of time of wound healing
- decrease of possibility of infection (no hematomes)
- possibility of application in endoscopy

In oncology the most important application of lasers is the photodynamic therapy (PDT), which is a non-invasive method of cancer operation. In ophtalmology lasers are used for therapy of glaucoma and foliation of retina. In dermatology lasers are used for destruction of pathologies on the skin's surface. In stomatology biostimulating lasers are applied for a non-invasive therapy of mucous membrane and caries. Laser light with high surface density of the power can also be applied for a non-invasive destruction of calculi in ureter and in urinary bladder. In gynaecology lasers are applied for therapy of diseases, which diminish fertility. These are just few examples from an ever-growing list.

In the diagnostic area endoscopic methods using laser light enable observation of internal organs of the body. These methods use optical waveguides to transmit the laser's light into the patient's body. Because of such a transmission internal organs of the body, like stomach, kidneys, urinary bladder, heart, blood vessels and so on, can be observed and diagnosed without a surgery. Therefore, it is of interest to study the structure and principle of operation of optical waveguides.

An optical waveguide cable is composed of following parts (from inside to outside – Figure 6): core, coat, varnish shell, protective coat, amplification layer and external sheath. To understand the principle of the waveguide's operation one can focus only on the core and the coat. The core is located in the middle of the cable and it is the medium transmitting the light signal. It is made of a quartz glass or plastic. The cores have the diameter of about 8 mikrometers for one-mode waveguides and about 1000 mikrometers for multimodal plastic waveguides. The coat is made of a material having the refraction index value (n) different than in case of the core.

The principle of operation of a waveguide is based on the phenomenon of the total internal reflection of the light. This phenomenon occurs on the interface separating two light-transparent phases having different values of the refraction index (n) and it can be observed from the phase with the higher value of the n. If the incidence angle of the light beam is higher than the boundary angle, the beam will be totally reflected from the interface without any refraction. The total internal reflection occurs on the interface between the core and the coat of the waveguide. Because of the total internal reflection, the light beam, which is transmitted inside the core, can not leave the core and it can be transmitted using waveguides for long distances.

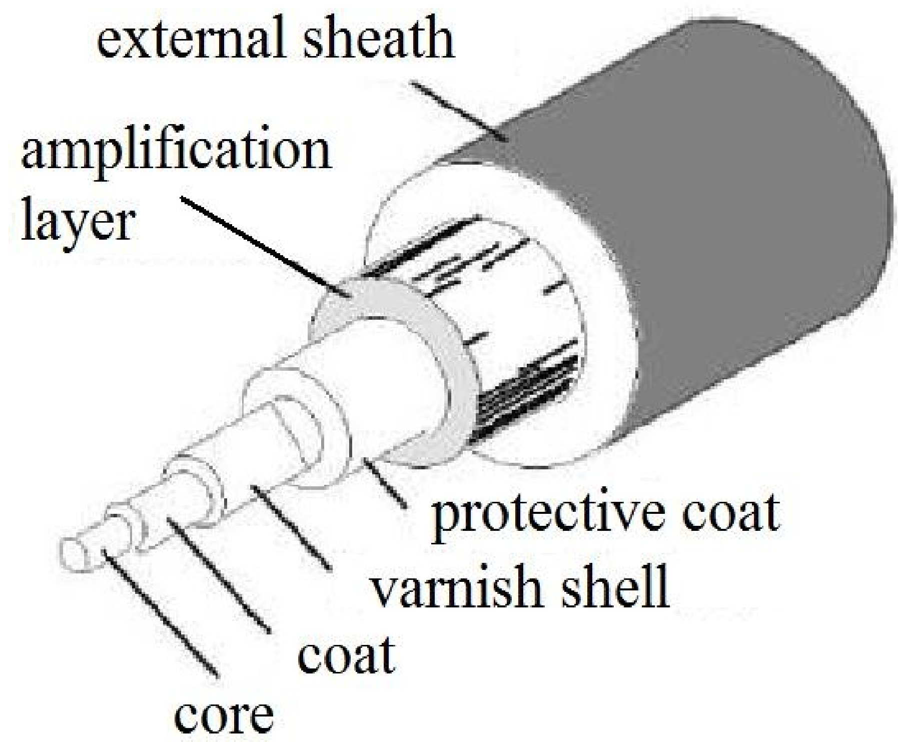

Figure 6. Structure of a waveguide.