Optics.

Optics is a part of physics investigating the generation, propagation and vanishing of light. The generation of light is also called **emission** and vanishing is also called **absorption** of light. The emission and absorption processes can be described by **particle** (quantum) model of light but the propagation of light is always described by the **wave** model. During its propagation, the light possesses all the properties of electromagnetic waves. So the principle of wave-particle duality is always actual in optics.

Electromagnetic wave is the propagation of the electromagnetic field in the space. The electric and magnetic fields that are changing in time are constantly generating each other. The electromagnetic (EM) waves are propagating in the substance with the speed $v = 1/(\varepsilon_0\varepsilon_r\,\mu_0\mu_r)^{1/2}$ where ε_0 and μ_0 are the permittivity and permeability constants, respectively (table *Physical quantities-electricity*). The quantities ε_r and μ_r are the relative permittivity and permeability of the substance. In the vacuum, the electromagnetic waves are propagating with the absolute speed (speed of light) $c = 1/(\varepsilon_0\mu_0)^{1/2}$.

Chart of the electromagnetic spectrum contains the following types of EM waves in the order of increasing frequency f (decreasing wavelength λ): radio waves, microwaves, infrared (IR) light, visible light, ultraviolet (UV) radiation, X-rays and gamma rays. The spectral parameters of the light are: wavelength in vacuum λ, frequency f, spectroscopic wavenumber k' ($k' = 1/\lambda$, most used unit 1 cm^{-1}) and quantum energy hf (unit 1 eV). The wavelength λ and the frequency f are related using the speed of light (c = 300 Mm/s) as follows: 1) in the cases of visible and IR light $f(\text{THz}) = (300\ \text{Mm/s}) / \lambda(\mu\text{m})$; 2) for the radio waves $f(\text{MHz}) = 300\ \text{Mm/s} / \lambda(\text{m})$. The wavelength λ and the quantum energy hf are related in following way: 1) for the visible and UV light $\lambda(\text{nm}) = (1240\ \text{nm}\cdot\text{eV}) / hf(\text{eV})$; 2) for the radio waves $\lambda(\text{mm}) = (1240\ \text{mm}\cdot\mu\text{eV}) / hf(\mu\text{eV})$; 3) for the X-rays $\lambda(\text{pm}) = (1240\ \text{pm}\cdot\text{keV}) / hf(\text{keV})$ and 4) for the gamma rays $\lambda(\text{fm}) = (1240\ \text{fm}\cdot\text{MeV})/hf(\text{MeV})$.

The intensity of light is the power of electromagnetic waves transferred per unit area, where the area is measured on the plane perpendicular to the direction of propagation of the energy. In the SI system, the intensity has a unit watts per square metre (W/m^2). Intensity can be found by multiplying of the energy density (energy of electromagnetic field per unit volume) by the velocity at which the energy is moving. The intensity is proportional to the electric or magnetic field strength squared.

Geometric optics is the part of optics using the concept of a light ray. It is the trace of light becoming observable as a result of the scattering. The geometric optics is the special case of the wave optics when the wavelength of light is so small that it can be considered equal to zero. The geometric optics is dealing with the optical equipment (lenses, mirrors, optical microscopes, telescopes, binoculars and so on).

The specular reflection is the mirror-like reflection of light from a surface, in which light from a single incoming direction (a ray) is reflected to a single outgoing direction. Such behavior of the light is described by the **law of reflection**, which states that the direction of incoming light (the incident ray), and the direction of outgoing light reflected (the reflected ray) form the same angle with respect to the surface normal, thus the angle of incidence equals the angle of reflection. The **normal** drawn in the point where the incident ray reaches the reflecting surface, the **incident** light ray and the **reflected** ray are all lying in the same plane.

Refraction is the change in direction of propagation of a light due to a change in its transmission medium. Due to the change of medium, the phase velocity of the wave is changed but its frequency remains constant. Refraction is described by Snell's law, which states that, for a given pair of a medium and a wave with a single frequency, the ratio of the sines of the angle of incidence θ_1 and angle of refraction θ_2 is a constant describing these two media which is called a **refractive index** of the second medium with respect of the first one n_{12} : $\sin\theta_1/\sin\theta_2 = n_{12}$. The absolute refractive index of the medium is the refractive index of this medium with respect to the vacuum. The relative refractive index n_{12} for the two media is equal to the ratio of speeds of light (v_1/v_2) in these two media. So the absolute refractive index of the medium n is equal to the ratio of speeds of light in vacuum and in this medium: $n = c/v$. Finally, the relative refractive index n_{12} is equal to the opposite ratio of the absolute refractive indices: $n_{12} = n_2/n_1$. In general, the incident light wave is always partially refracted and partially reflected.

Maxwell refraction formula states that the absolute refractive index n of the non-magnetic ($\mu_r = 1$) substance is equal to the square root of the relative permittivity ε_r of the substance: $n = \varepsilon_r^{1/2}$. The optical properties of the substance are determined by its electrical properties.

Total internal reflection is the phenomenon which occurs when a propagated wave strikes a medium boundary at an angle larger than a particular **critical angle** with respect to the normal to the surface. If the refractive index is lower on the other side of the boundary and the incident angle is greater than the critical angle, the wave cannot pass through and is entirely reflected. This can only occur when the wave in a medium with a higher refractive index (n_1) reaches a boundary with a medium of lower refractive index (n_2). For example, it will occur with light reaching air from glass, but not when reaching glass from air. The light is propagating in the **optical fibers** using total internal reflection.

Wave optics is investigating the phenomena which can be described using the wave theory of light. They are predominantly the interference, diffraction and polarization.

Interference of the light is a phenomenon in which two light waves superpose to form a resultant wave. When interfering, two waves can add together to create a wave of greater amplitude than either one (to form a interference maximum) or subtract from each other to create a wave of lower amplitude than either one (to form a minimum). The redistribution of the energy of light waves always take place as a result of the interference. In the regions, where the maxima of two waves coincide, the **constructive** interference occur. The spatial density of the energy of the light waves is bigger than its mean value. In the regions, where the maximum of one wave coincides with the minimum of another one, the **destructive** interference occurs. Two waves cancel each other, the energy density of the waves is lower than its mean value. With the certain final result, only **coherent** waves can interfere. Two wave sources are perfectly coherent if they have a constant phase difference and the same frequency.

Diffraction refers to various phenomena which occur when a light wave encounters an obstacle or a slit. It is defined as the bending of light around the corners of an obstacle or aperture into the region of geometrical shadow of the obstacle. While diffraction occurs always, its effects are generally most pronounced for waves whose wavelength is roughly comparable to the dimensions of the diffracting object or slit. In the case of diffraction of the plane wave penetrating a single slit, the first **minimum** is located at the angle φ with respect to the diffraction pattern centre. This angle is determined by the condition $\sin \varphi = \lambda / b$, where λ is the wavelength of the light used and b is the width of the slit.

Diffraction grating is a system containing a lot of periodically located slits. The distance between the similar points of the neighbouring slits is called **period** d of the grating. The period is a sum of the width of the slit and the width of non-transmittable area between the two neighbouring slits. The colored **maxima** are located at the some angles φ with respect to the diffraction pattern centre. These angles are determined by the formula of diffraction grating $m\lambda = d \sin \varphi$, where λ is the wavelength of the light used and m is an integer number (the order of spectrum). Because the diffraction angle φ depends on the wavelength λ of the light, the grating acts as the dispersive element, splitting light into several coloured beams travelling in different directions.

Polarization is a parameter applying to the light waves that specifies the geometrical orientation of the oscillation. In an electromagnetic wave, both the electric and magnetic field are oscillating but in different directions. By convention, the polarization of light refers to the polarization of the electric field. The oscillation of electric field may be in a single direction (**linear** polarization), or the field vector may rotate at the frequency of the wave (**circular** or **elliptical** polarization). Look at the differences between the various types of polarization: http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/polclas.html

Polarizer is an optical filter that lets light waves of a specific polarization pass and blocks light waves of other polarizations. It can convert a beam of light of undefined or mixed polarization into a beam of well-defined polarization, that is polarized light. The two main types of polarizers are beam-splitting polarizers and birefringent polarizers. **Beam-splitting** polarizers split the incident beam into two beams of differing linear polarization. The differences between polarization conditions of reflected and refracted light are used. When light reflects from an interface between two transparent materials, the reflectivity is different for light polarized in the plane of incidence and light polarized perpendicular to it.

Birefringence is the optical property of a material having a refractive index that depends on the polarization and propagation direction of light. Birefringence is responsible for the phenomenon of double refraction whereby a ray of light, when incident upon a birefringent material, is split by polarization into two rays taking slightly different paths. If we look through a birefringent material, we see all the objects twice.

Optical rotation or **optical activity** is the rotation of the plane of polarization of linearly polarized light as it travels through certain materials. Optical activity occurs only in chiral materials, those lacking microscopic mirror symmetry. The rotation of the plane of polarization may be either clockwise, to the right (d-rotary), or left (l-rotary) depending on which stereoisomer is dominant. For a given substance, the angle by which the polarization of light of a specified wavelength is rotated is proportional to the path length through the material and (for a solution) proportional to its concentration. Modulation of optical activity of a liquid crystal, viewed between two sheet polarizers, is the principle of operation of liquid-crystal displays (LCD) used in most modern televisions and computer monitors.

Dispersion of the light is the phenomenon in which the phase velocity of a light wave and also the refractive index n of the light-carrying medium depends on the frequency of light. Media having this common property are called *dispersive media*. Dispersion is caused by the interaction of electromagnetic waves with oscillating charged particles in the substance. They are forced oscillations and the electric field of the electromagnetic wave $E = E_m \sin \omega t$ is acting as a periodical outer force. At some frequency ω_r, the resonance takes place. The charged particles can oscillate as: 1) the free charge carriers (conduction electrons), 2) the bound charge carriers (valence electrons) or 3) the ions in the ionic crystals. All these types of oscillations have characteristic resonance frequencies which are determining the shape of the dispersion curve $n = n(\omega)$.

Absorption of the light is the process in which the energy of light is transformed into internal energy of the absorbing substance, for example thermal energy. The intensity of light I is decreasing during the absorption according to the **Bouguer-Lambert-Beer** law: $I(l) = I_0 e^{-\kappa l}$ where $I(l)$ is the intensity of light at the distance l from the surface of absorbing medium, I_0 is the intensity of the incident light and κ is the absorption coefficient typically measured in units of reciprocial centimeters (1 cm^{-1}). The value of **absorption coefficient** κ means that the intensity will be reduced Euler number (e = 2.7183) times when the light passes through the $1/\kappa$ cm thick layer of the substance (the product $\kappa l = 1$ and $I_0/I = e$).

Colour of the substance is determined by the absorption spectrum of the substance. It is the dependence of the absorption coefficient on some spectral parameter of the light. The colour of the light which is **not** absorbed by the substance is really the colour of this substance.

The photoelectric effect or *photoemission* is the production of electrons or other free carriers when light is incident upon a substance. Electrons emitted in this manner can be called *photoelectrons*. According to the classical physics, this effect can be attributed to the transfer of energy from the light to an electron. An alteration in the intensity of light would induce changes in the rate of photoemission. However, the experiments show very clearly that the photoemission is possible only if the frequency of the light exceeds some threshold level. Below that threshold, no electrons are emitted from the metal regardless of the light intensity or the length of time of exposure to the light. The maximum kinetic energy E_k of the photoelectron depends in linear way on the frequency f according to the photoelectric equation by Albert Einstein: $E_k = hf - \phi$. Here h is the **Plank constant** ($h = 6.626*10^{-34}$ J s) and ϕ is the **work function** (the minimum energy required to eject an electron from the metal surface). We also see that the threshold frequency f_{min} is determined by the work function: $f_{min} = \phi/h$ (if $E_k = 0$).

The photovoltaic effect is the creation of voltage or electric current in a material upon exposure to light. The light is absorbed, causing excitation of an electron or other charge carrier to a higher-energy state. An electric voltage is produced by the separation of charge carriers when the light has a sufficient quantum energy to overcome the potential barrier for separation. When light is incident upon the solid, the valence electrons absorb energy and become free. This generates an electromotive force, and thus some of the light energy is converted into electric energy.

Optoelectronics is the study and application of electronic devices and systems that act as a light source or detect and control light. Most well known optoelectronic devices are light emitting diode (LED), semiconductor laser and solar cell.

The light emitting diode (LED) is a forward biased PN junction which generates light using the energy of electric field. PN junction is the region in the semiconductor where n-conducting and p-conducting parts are in contact. In n-conducting part, the dominating charge carriers are (negative) electrons. In the p-conducting part the dominating carriers are (positive) holes. In the case of forward biasing, the positive pole of outer voltage source is connected to the p-conducting part of semiconductor, and the negative pole of the source is is connected to the n-conducting part. The electric field generated by the source is bringing the electrons and holes together. When an electron meets the hole, then the hole is filled by the electron and the energy of electron-hole pair is transmitted to the generated photon. The semiconductor laser is simply the LED which is working in the laser regime (put into an optical cavity).

Solar cell is converting light energy into electric energy using the photovoltaic effect in a PN junction. The photons absorbed in the region of PN junction generate the electron-hole pairs. The electric field of the PN junction separates the electron and hole components of the pairs. As a result, the electromotive force is created.

Thermal radiation is electromagnetic radiation generated by the thermal motion of charged particles in matter. All matter with a temperature greater than absolute zero emits thermal radiation. Examples of thermal radiation include the light emitted by an incandescent light bulb, the infrared radiation emitted by animals, and the cosmic microwave background radiation. Sunlight is part of thermal radiation generated by the hot plasma of the Sun. The Earth also emits thermal radiation, but at a much lower intensity and different spectral distribution because it is cooler. The Earth's absorption of solar radiation, followed by its outgoing thermal radiation are the two most important processes that determine the temperature and climate of the Earth. Thermal radiation is the most effective mechanism of heat transfer.

Black-body radiation is the electromagnetic radiation emitted by a black body being in thermodynamic equilibrium with its environment. **Black body** is a body which is able to absorb whole incident light. The radiation has a specific spectrum and intensity that depends only on the temperature of the body. A black body at room temperature appears black, as most of the energy it radiates is infra-red and cannot be perceived by the human eye. When it becomes a little hotter, it appears dull red. As its temperature increases further it eventually becomes blue-white.

The radiant emittance R, also known as the *surface radiance* or *radiant exitance* of a black body is the total energy radiated in all directions per unit surface area of a black body across all wavelengths or frequencies per unit time. The radiant emittance is measured in watts per square meter (W/m^2). The spectral radiance is defined either as the radiant emittance per unit interval of wavelengths $\mathrm{d}R/\mathrm{d}\lambda$ at some fixed value of wavelength λ, or the radiant emittance per unit interval of frequencies $\mathrm{d}R/\mathrm{d}f$. The radiant emittance is the integral of the spectral radiance function over all the wavelengths or frequencies.

The Stefan-Boltzmann law describes the power radiated from a black body in terms of its temperature. The Stefan-Boltzmann law states that the radiant emittance of the black-body is directly proportional to the fourth power of the black body's thermodynamic temperature T: $R = \sigma T^4$. The constant σ is called the Stefan–Boltzmann constant and its value is $\sigma = 5{,}67 \cdot 10^{-8}$ W/($m^2 K^4$). A body that does not absorb all incident radiation is known as a **grey body** and it emits less total energy than a black body.

Wien's displacement law states that the spectral radiance curve $\mathrm{d}R/\mathrm{d}\lambda$ of the black body for different temperatures peaks at a wavelength λ_{max} inversely proportional to the temperature T: $\lambda_{max} = b/T$. The constant b is called Wien's displacement constant and it is equal to $2.898 \cdot 10^{-3}$ m · K, or more conveniently to obtain wavelength in micrometers, $b \approx 2900$ µm·K.

Luminescence is emission of light by a substance not resulting from heat; it is thus a form of cold-body radiation. It can be caused by chemical reactions, electrical energy, subatomic motions, or stress on a crystal. This distinguishes luminescence from thermal radiation, which is light emitted by a substance as a result of heating. The energy needed for luminescence can be transmitted to the emitting substance in various ways defining the types of luminescence. It can be done: 1) by the another light possessing bigger quantum energy (then we speak about photoluminescence), 2) by the electric field (electroluminescence); 3) by the chemical reaction (chemiluminescence); 4) as a result of mechanical action on the solid (mechanoluminescence); 5) as a result of a luminescent material being struck by high-energy electrons (cathodoluminescence); 6) as a result of bombardment by ionizing radiation (radioluminescence).

According to the typical duration of the luminescence process or the lifetime of the excited state, the photoluminescence is divided into: a) fluorescence (the lifetime of the excitation is short, typically some nanoseconds); b) phosphorescence (the lifetime of the excitation is long, typically milliseconds to hours). The special case of the photoluminescence is the Raman emission – an inelastic scattering of laser light by some substance. In this case the rotational or vibrational energies of molecules are added to the laser photon energy or subtracted from it. The frequency shift of some Raman line with respect to the exciting light frequency provides information about the rotational or vibrational energy levels.

Laser is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation. The term *laser* originated as an acronym for *light amplification by stimulated emission of radiation*. A laser differs from other sources of light in that it emits light coherently. Spatial coherence allows a laser to be focused to a tight spot. It also allows a laser beam to stay narrow over great distances, enabling applications such as laser pointers. Lasers can also have high temporal coherence, which allows them to emit light with a very narrow spectrum, i.e., they can emit a single color of light. Temporal coherence can be used to produce pulses of light as short as a femtosecond.

Working principle of a **laser** is based on: a) the inversion created in the quantum system and b) use of the optical cavity. The inversion means that the higher energy level is occupied more probably than the lower levels. There are a lot of particles ready to emit light quanta with certain properties (frequency, phase and polarization). In the lasers, the system generating the inversion (the pumping system) should be always in use. An **optical cavity** is an arrangement of mirrors that forms a standing wave. Light confined in the cavity reflects multiple times on the mirrors producing standing waves for certain resonance frequencies. So the probability for generating a twin for some photon always existing in the cavity, is enhanced.

Lasers are used in optical disk drives, laser printers, and barcode scanners; DNA sequencing instruments, fiber-optic and free-space optical communication; laser surgery and skin treatments; cutting and welding materials; military and law enforcement devices for marking targets and measuring range and speed; and laser lighting displays in entertainment.