Chapter

Electromagnetic Waves

Ivo Čáp, Klára Čápová, Milan Smetana and Štefan Borik

1. Introduction

There exist various forms of energy in the universe, for example, the kinetic and potential energy of bodies, the internal energy of substances, associated with bonding and microscopic motion of atoms and molecules, nuclear energy associated with atomic nuclei composition, the energy of the gravitational and electromagnetic field. The universal law of energy conservation expresses that energy cannot arise or disappear, and it can only change from one form to another. An important part of the energy of the universe is electromagnetic energy that we perceive through various electrical, magnetic, and electromagnetic phenomena. They are widely used in biomedicine both in diagnostics, e.g., thermography, microscopy, MRI, endoscopy, fluoroscopy, computed tomography, PET, SPECT, and in therapy, e.g., diathermy, microwave hyperthermia, phototherapy, laser scalpel, exposition to ionizing radiation. We present an overview of basic knowledge, which provides a deeper understanding of biomedical applications of electromagnetic waves and the possibilities of their practical use, see also Rajeev [1, 2], Someda [3].

Classical electrodynamics is based on the definition of the basic field quantities, which are the intensity of electric field $\boldsymbol{E}$ and induction of the magnetic field $\boldsymbol{B}$, defined by the force $\boldsymbol{F}$ of the electromagnetic (EM) field on a particle with a charge Q moving at velocity $\boldsymbol{v}$ by the Lorentz relation

$$\boldsymbol{F} = Q\boldsymbol{E} + Q\ \boldsymbol{v} \times \boldsymbol{B}. \tag{1}$$

In addition to the electric charge, the particles also have a magnetic dipole moment $\boldsymbol{m}$, which describes another type of interaction of a particle, of a magnetic dipole, with a magnetic field with the induction $\boldsymbol{B}$ by.

$$\boldsymbol{M} = \mathbf{m} \times \boldsymbol{B}, \quad \boldsymbol{F} = \mathbf{m}\ \text{grad}\ \boldsymbol{B}, \quad E_{\text{p}} = -\mathbf{m} \cdot \boldsymbol{B} + \boldsymbol{E}_{\text{p}0}, \tag{2}$$

where $\boldsymbol{M}$ is the moment (torque) of the force $\boldsymbol{F}$ exerting on the dipole, and E_{p} is the potential energy of the magnetic dipole in the magnetic field.

In addition to the primary quantities $\boldsymbol{E}$, $\boldsymbol{B}$, other ones, electric induction $\boldsymbol{D}$, and magnetic intensity $\boldsymbol{H}$, are defined. They take the properties of the medium into account, in which we follow the EM field.

The classical description of the EM field is based on Maxwell's equations

$$\mathbf{curl}\,\mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}, \tag{3}$$

$$\mathbf{curl}\,\mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \tag{4}$$

$$\text{div}\,\mathbf{B} = 0, \tag{5}$$

$$\text{div}\,\mathbf{D} = \rho, \tag{6}$$

where $\boldsymbol{J}$ is the current density of free charge carriers and ρ is the free charge density.

The quantities $\boldsymbol{D}$ and $\boldsymbol{E}$, and quantities $\boldsymbol{H}$ and $\boldsymbol{B}$ are mutually connected by the material relations, which reflect the properties of the medium as homogeneity-inhomogeneity, linearity-nonlinearity, isotropy-anisotropy, etc.

In the case of a linear, homogeneous, and isotropic medium are valid simple relations between the field quantities.

$$\boldsymbol{B} = \mu\, \boldsymbol{H}, \boldsymbol{D} = \varepsilon\, \boldsymbol{E}, \tag{7}$$

where constant coefficients μ, ε are permeability and permittivity of the medium. The current density has two components.

$$\boldsymbol{J} = \boldsymbol{J}_0 + \gamma\, \boldsymbol{E}, \tag{8}$$

where $\boldsymbol{J}_0$ is the current density of the forced source current, the component $\gamma\, \boldsymbol{E}$ is the current density of the passive current induced by the electric field in the conductive medium, and γ is the conductivity of the medium.

From the Maxwell Eqs. (3) and (4), using relations (7) and (8), we can express separately the equation for electric intensity $\boldsymbol{E}$ and magnetic induction $\boldsymbol{B}$. In the first Maxwell equation we differentiate according to time, on the second one we apply operator **curl,** and we consider the relation $\partial/\partial t$ **curl** $\boldsymbol{B}$ = **curl** $\partial \boldsymbol{B}/\partial t$

$$\frac{\partial}{\partial t}\ \mathbf{curl}\ \mathbf{B} = \mu\ \frac{\partial \mathbf{J}_0}{\partial t} + \mu\gamma\ \frac{\partial \mathbf{E}}{\partial t} + \mu\varepsilon\ \frac{\partial^2 \mathbf{E}}{\partial t^{\ 2}}, \tag{9}$$

$$\mathbf{curl}\ \mathbf{curl}\ \mathbf{E} = -\mathbf{curl}\ \frac{\partial \mathbf{B}}{\partial t} = \mathbf{grad}\ \mathrm{div}\ \mathbf{E} - \Delta\mathbf{E} \tag{10}$$

We get the equation

$$\Delta\,\mathbf{E} - \mu\gamma\ \frac{\partial \mathbf{E}}{\partial t} - \mu\varepsilon\ \frac{\partial^2 \mathbf{E}}{\partial t^{\ 2}} = \mu\ \frac{\partial \mathbf{J}_0}{\partial t} + \mathbf{grad}\ \frac{\rho}{\varepsilon}. \tag{11}$$

In the same way, we get the equation for magnetic induction

$$\Delta\mathbf{B} - \mu\gamma\ \frac{\partial \mathbf{B}}{\partial t} - \mu\varepsilon\ \frac{\partial^2 \mathbf{B}}{\partial t^{\ 2}} = -\mu\ \mathbf{curl}\,\mathbf{J}_0. \tag{12}$$

The left sides of the equations are typical for the wave equation (compare with the mechanical one). They are wave equations of a damped wave. The right sides of the equations represent the source functions of the wave. The source of the EM field is the gradient of charge density and the charge movement described by the curl of the current density. Nonhomogeneous distribution of charge is the source of the electrostatic field component, while the charge motion is the source of the magnetic component of the electromagnetic field. From the equations (11) and (12) follows that the EM field propagates in space as a wave and the electric component, given by the vector $\boldsymbol{E}$, and magnetic component given by the vector $\boldsymbol{B}$, have the common space-time dependence and represent only one physical object—the electromagnetic wave. In the space out of the source, the right sides of the wave equations are equal to zero, from which follows that EM wave can propagate in the space independently without the presence of other sources.

1.1 Plane electromagnetic wave

The basic characteristics of EM wave best explain the simplest example of the plane wave, in which the quantities depend only on one space variable z-coordinate in the direction of the wave propagation. The plane wave quantities $\boldsymbol{E}$ and $\boldsymbol{B}$ are not dependent on space coordinates x and y in the directions perpendicular to the wave propagation direction.

Let us consider the wave which propagates in linear homogeneous and isotropic medium out of sources (where ε, μ, g are constants, $\rho = 0, \boldsymbol{J}_0 = 0$). Under these assumptions, the Maxwell equations have the form

$$-\frac{\partial B_x}{\partial z}\ \mathbf{y}^0 + \frac{\partial B_y}{\partial z}\ \mathbf{x}^0 = \mu\gamma\ \left(E_x\mathbf{x}^0 + E_y\mathbf{y}^0 + E_z\mathbf{z}^0\right) + \mu\varepsilon\ \frac{\partial}{\partial t}\left(E_x x^0 + E_y\mathbf{y}^0 + E_z\mathbf{z}^0\right)$$

$$-\frac{\partial E_x}{\partial z}\ \mathbf{y}^0 + \frac{\partial E_y}{\partial z}\ \mathbf{x}^0 = -\mu\ \frac{\partial}{\partial t}\left(B_x x^0 + B_y\mathbf{y}^0 + B_z\mathbf{z}^0\right),$$

$$\frac{\partial E_z}{\partial z} = 0 \text{ and } \frac{\partial B_z}{\partial z} = 0,$$

where $\boldsymbol{x}^0, \boldsymbol{y}^0, \boldsymbol{z}^\mathbf{0}$ are unit vectors in the directions x, y, z of a rectangular coordinate system.

Comparing the vector components of both sides of the equations we get.

$$\frac{\partial B_y}{\partial z} = \mu\varepsilon\ \frac{\partial E_x}{\partial t},\ -\frac{\partial B_x}{\partial z} = \mu\varepsilon\ \frac{\partial E_y}{\partial t}, \tag{13}$$

$$\frac{\partial E_y}{\partial z} = -\mu\ \frac{\partial B_x}{\partial t},\ -\frac{\partial E_x}{\partial z} = -\mu\ \frac{\partial B_y}{\partial t}, \tag{14}$$

$$0 = \mu\varepsilon\ \frac{\partial E_z}{\partial t}, \frac{\partial E_z}{\partial z} = 0, 0 = -\mu\ \frac{\partial B_z}{\partial t}, \frac{\partial B_z}{\partial z} = 0. \tag{15}$$

From Eq. (15) follow that the time and space-dependent longitudinal components of electric intensity and magnetic induction are zero. Non-zero wave components are only transversal ones.

Let us apply the axes x, y, z in the way, that axis x has the direction of the vector of electric intensity, which means $\boldsymbol{E} = E_z\,\boldsymbol{x}^0$, and $E_y = 0$. It results from the Eqs. (13) and (14) that wave component $B_z = 0$. Magnetic induction is then $\boldsymbol{B} = B_y\,\boldsymbol{y}^0$.

The electromagnetic wave has transversal polarization, vectors $\boldsymbol{E}, \boldsymbol{B}$ are mutually perpendicular and perpendicular to the direction of wave propagation.

Eqs. (11) and (12) have the form

$$\frac{\partial^2 E_x}{\partial z^{\ 2}} - \ \mu\gamma\ \frac{\partial E_x}{\partial t} - \mu\varepsilon\ \frac{\partial^2 E_x}{\partial t^{\ 2}} = 0, \qquad E_y = E_z = 0, \tag{16}$$

$$\frac{\partial^2 B_y}{\partial z^{\ 2}} - \ \mu\gamma\ \frac{\partial B_y}{\partial t} - \mu\varepsilon\ \frac{\partial^2 B_y}{\partial t^{\ 2}} = 0, \qquad B_x = B_z = 0. \tag{17}$$

1.1.1 Plane EM wave in a lossless medium

In the medium with the non-zero conductance, $\gamma \neq 0$, arises electric current with the current density $\boldsymbol{J}$. The current in the material relates to the transformation of EM wave energy into heat. This energy loss causes EM wave attenuation.

If the medium conductance is zero (vacuum or the ideal dielectrics), $\gamma = 0$, the plane wave equations have the form

$$\frac{\partial^2 \mathbf{E}}{\partial z^{\ 2}} - \mu\varepsilon\ \frac{\partial^2 \mathbf{E}}{\partial t^{\ 2}} = 0, \tag{18}$$

$$\frac{\partial^2 \mathbf{B}}{\partial z^{\ 2}} - \mu\,\varepsilon\ \frac{\partial^2 \mathbf{B}}{\partial t^{\ 2}} = 0. \tag{19}$$

These are wave equations of a non-damped EM wave that propagates in the direction of the z- axis with a speed

$$c = \sqrt{\frac{1}{\mu\,\varepsilon}} = \sqrt{\frac{1}{\mu_0\,\varepsilon_0}}\ \frac{1}{\sqrt{\mu_{\rm r}\,\varepsilon_{\rm r}}} = \frac{c_0}{n}, \tag{20}$$

where c_0 is the speed of EM wave in a vacuum and $n = \sqrt{\mu_{\rm r}\,\varepsilon_{\rm r}}$ is the absolute refraction index of the medium in which the wave propagates. If the medium is homogeneous one, and the refraction index is independent on frequency, i.e., n = const., the generated EM wave propagates in space with the speed c without any distortion.

Example 1. Propagation of EM wave in a dielectric medium.

As an example, we introduce the speed of EM wave in vacuum (ε_0 = 8.85 × 10^{-12} F m^{-1}, μ_0 = 4π × 10^{-7} H m^{-1}), c_0 = 3.00 × 10^8 m s^{-1}).

At the frequency of 100 Hz is the relative permittivity of water $\varepsilon_{\,\mathrm{r}1}$ = 81 and $\mu_{\,\mathrm{r}}$ = 1, i.e., the refraction index $n_1 \sim 9.0$, and the speed of the EM wave c_1 = 3.3 × 10^7 m s^{-1}.

The relative permittivity of water depends on frequency. In the optical range of frequencies, the relative permittivity $\varepsilon_{\mathrm{r}2}$ = 1.77, refraction index $n \approx 1.33$, and the speed of light c_2 = 2.25 × 10^8 m s^{-1}.

Glass refraction index n = 1.5–1.9 according to the sort of glass, i.e., the speed of light $c \approx$ (1.58–2.00) × 10^8 m s^{-1}.

Air refraction index at the standard conditions n = 1.00059, i.e., the speed of EM wave in the air is c = 2.99283 × 10^8 m s^{-1}. For most of the applications is used $c \approx c_0$. When considering inhomogeneity of the air or a wave dispersion, it is necessary to take the speed of light in the air with an accuracy of 5 decimal numbers.

1.1.2 Harmonic plane electromagnetic wave

1.1.2.1 Wave function of harmonic EM wave

If the exciting current of the EM wave has the harmonic time dependence with the angular frequency ω, then in a linear medium, all quantities of EM field also have the harmonic time dependence with the same angular frequency ω. Let us consider the EM wave in the loss medium.

The complex harmonic functions we express by relations.

$$\mathbf{E}(z,t) = \mathbf{E}\,(z)\ \ \mathrm{e}^{\mathrm{j}\,\omega\,t}, \mathbf{H}(z,t) = \mathbf{H}\,(z)\ \ \mathrm{e}^{\mathrm{j}\,\omega\,t}, \tag{21}$$

where $\mathbf{E}(z)$, $\mathbf{H}(z)$ are phasors of the EM wave.

The complex quantities we introduce into wave equations (11) and (12), we realize time derivatives and reduce time function.

For the wave out of the source, we get equations for the phasors of the field quantities

$$\frac{\mathrm{d}^2\mathbf{E}(z)}{\mathrm{d}z^2} - \left(\mathrm{j}\omega\mu\gamma - \omega^2\mu\,\varepsilon\right)\ \mathbf{E}(z) = 0, \tag{22}$$

$$\frac{\mathrm{d}^2\mathbf{H}(z)}{\mathrm{d}z^2} - \left(\mathrm{j}\omega\mu\gamma - \omega^2\mu\,\varepsilon\right)\ \mathbf{H}(z) = 0. \tag{23}$$

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Their solutions are the following functions.
$\mathbf{E}(z) = \mathbf{E}_m \ e^{\pm \mathbf{k} z}$, $\mathbf{H}(z) = \mathbf{H}_m \ e^{\pm \mathbf{k} z}$, where

$$\mathbf{k} = \sqrt{j \, \omega \mu \, (\gamma + j \, \omega \varepsilon)} = \beta + j \, \alpha \tag{24}$$

is complex propagation constant of the EM wave.
The complex wave functions are

$$\mathbf{E}(z,t) = \mathbf{E}_m^+ \ e^{-\beta z} \ e^{j(\omega t - \alpha z)} + \mathbf{E}_m^- \ e^{\beta z} \ e^{j(\omega t + \alpha z)} \tag{25}$$

$$\mathbf{H}(z,t) = \mathbf{H}_m^+ \ e^{-\beta z} \ e^{j(\omega t - \alpha z)} + \mathbf{H}_m^- \ e^{\beta z} \ e^{j(\omega t + \alpha z)}. \tag{26}$$

The relations consist of a superposition of direct and reflected waves. The phase argument $\omega t - a z$ represents the direct wave propagating in the z-direction, and argument $\omega t + a z$ is the reflected wave in the opposite direction. Both waves exponentially damp in their propagation directions with the attenuation factor β.

The real and imaginary parts of the coefficient $\mathbf{k}$ we obtain by decomposition of the definition relation (24)

$$\mathbf{k}^2 = j \, \omega \mu \, (\gamma + j \, \omega \varepsilon) = \beta^2 - \alpha^2 + j \, 2\alpha\beta. \tag{27}$$

By comparing real parts and imaginary parts on the left and right side we get two equations for α and β, from which we get

$$\beta = \sqrt{\frac{\omega^2 \mu \varepsilon}{2}} \ \sqrt{-1 + \sqrt{1 + \left(\frac{\gamma}{\omega \varepsilon}\right)^2}}, \tag{28}$$

$$\alpha = \sqrt{\frac{\omega^2 \mu \varepsilon}{2}} \ \sqrt{1 + \sqrt{1 + \left(\frac{\gamma}{\omega \varepsilon}\right)^2}}. \tag{29}$$

The attenuation coefficient β determines the effective wave propagation length $\delta = 1/\beta$, at which the amplitude of the wave decreases due to the attenuation in the ratio $e^{-1} \approx 37\%$.

The coefficient α determines the wavenumber,

$$\textit{the wavelength } \lambda = \frac{2\pi}{\alpha}, \text{and the } \textit{phase velocity of the wave } c = \frac{\omega}{\alpha}. \tag{30}$$

EM waves can propagate in free space, e.g., light from a light source, or in wires, e.g., two-wire line, coaxial line, waveguide, optical fiber, etc. In the case of EM wave propagation in confined structures, the propagation parameters (phase velocity and attenuation) also depend on the geometrical arrangement of the line.

1.1.2.2 EM wave propagation in a low-loss medium

In the case of a low-loss medium, for which $\gamma \ll \omega \varepsilon$ at low conductivity γ of the medium, and/or high-frequency ω, the propagation constants α and β are given by approximate relations

$$\beta \approx \frac{\gamma}{2} \ \sqrt{\frac{\mu}{\varepsilon}}, \qquad \alpha = \omega \sqrt{\mu \varepsilon} \ , \tag{31}$$

from which we get the phase velocity c of the wave and the effective propagation length δ.

$$c = \frac{1}{\sqrt{\mu\,\varepsilon}} = \frac{1}{\sqrt{\mu_0\,\varepsilon_0}}\ \frac{1}{\sqrt{\mu_r\,\varepsilon_r}} = \frac{c_0}{n}, \text{ and } \delta \approx \frac{2}{\gamma}\ \sqrt{\frac{\varepsilon}{\mu}}. \tag{32}$$

If the material parameters of the medium are constant, then both quantities are constant and independent of the frequency. However, when moving from one frequency domain to another, e.g., from the radio waves to the optical region, the parameters may change significantly, resulting in a change in phase velocity and effective wave propagation length.

1.1.2.3 EM wave propagation in a conductive medium

In the case of a conductive medium where $\gamma \gg \omega\,\varepsilon$, the propagation coefficients are given by approximate relations.

$$\beta \approx \sqrt{\frac{\omega\mu\,\gamma}{2}} \text{ and } \alpha \approx \sqrt{\frac{\omega\mu\,\gamma}{2}}\ . \tag{33}$$

Effective wave propagation length $\delta \approx \sqrt{\frac{2}{\omega\mu\,\gamma}}$ decreases with increasing frequency.

The phase velocity of a wave $c = \frac{\omega}{\alpha} = \sqrt{\frac{2\omega}{\mu\gamma}}$ depends on the frequency.

The wavelength $\lambda = \frac{2\pi}{\alpha} = 2\pi\ \delta$, i.e., the length δ is about 1/6 of λ.

Example 2. EM wave in a conductor.

Consider an EM wave with a frequency of 10 MHz propagating in the copper with γ = 56 MS m^{-1}, and μ_r = 1.00. The wave propagates in the medium as damped one with parameters: $\delta \approx$ 21.3 μm, $c \approx$ 1340 m s^{-1}, λ = 134 μm.

As a result, we can see that the EM wave incident on the surface of the metal penetrates only a very thin surface layer. This effect calls the *skin effect*.

The penetrating EM wave causes an eddy current in the surface layer of the conductor. Due to the current flow, the energy of the EM wave changes into heat in the medium. This loss of energy causes wave attenuation. On passing the depth δ, the amount of 86% of the EM wave power penetrating the conductor is consumed. Changing the frequency allows controlling the penetration depth δ. The absorption of wave energy is utilized for heating conducting bodies. For example, a microwave oven uses an EM field with a frequency of 2.45 GHz. Assuming a meat conductivity of approximately 0.1 S m^{-1}, we obtain $\delta \approx$ 3 cm. So, the heat is releases in a thick surface layer of the meat, and the whole volume warms. In the case of a grill that uses infrared radiation with a wavelength of about 10 μm (f = 30 THz), we have $\delta \approx$ 0.3 mm. In this case, the wave energy converts to heat in a very thin surface layer, and such a crispy crust arises. The rest of the meat volume is then warmed by the heat conduction from the surface to the inside. In medicine, the heating of tissues is used for therapeutic purposes.

Hyperthermia (tissue warming) aims to destroy the tumors, which are sensitive to overheating. By selecting a suitable frequency, one can adjust the action to the required depth below the surface of the body.

Thermotherapy utilizes stimulation of some physiological processes and, in such a way, speeds up the treatment (e.g., diathermy using EM waves up to tens of MHz, hyperthermia using microwave radiation, phototherapy using optical radiation, etc.).

A thin layer of skin protects the subcutaneous organs from the effects of light and UV radiation. A thin layer of eyelids protects the eye from the direct influence of sunlight (looking into the sun with the eyelids closed). Protecting the body against overheating by the direct impact of intensive radiation realizes sweating due to the conversion of the absorbed energy into the latent heat of evaporation.

The electrical conductivity of the tissue varies with the frequency. At frequencies above the infrared band, the conductivity significantly drops. Despite the increasing frequency, the effective depth of the wave penetration increases. While ultraviolet radiation has an effective penetration depth of less than 1 mm, that of X-rays is of about tens centimeters, which allows imaging of body structures by transmission radiology (X-ray, CT-Computed Tomography), utilizing different attenuation of radiation in different tissues.

1.1.2.4 Dielectric parameters of substances

In biomedical applications, we are interested in the propagation of EM waves in non-magnetic media with relative permeability $\mu_r = 1$. Substances thus describe the relative permittivity ε_r and the conductivity γ. We often consider tissues or the surrounding media as lossy dielectrics.

For the harmonic wave, the first Maxwell equation has a form

$$\mathbf{curl}\,\mathbf{H} = \gamma\,\mathbf{E} + \mathrm{j}\omega\varepsilon\,\mathbf{E} = \mathrm{j}\omega\varepsilon_0\left(\varepsilon_r - \mathrm{j}\frac{\gamma}{\omega\varepsilon_0}\right) = \mathrm{j}\omega\,\varepsilon_0\,\boldsymbol{\varepsilon}_r, \tag{34}$$

where $\boldsymbol{\varepsilon}_r = \varepsilon_r' - \mathrm{j}\varepsilon_r''$ is a complex relative permittivity. The real part ε_r' determines the displacement current in the substance, the imaginary part ε_r'' is called the loss factor, and it is related to the attenuation of the wave by the conversion of the EM field energy into heat. Quantities ε_r', ε_r'', and γ are complicated functions of the frequency of the harmonic wave.

The permittivity of the substances is influenced by internal relaxation processes, especially in liquid substances, that characterizes the relationship

$$\boldsymbol{\varepsilon}_r = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + \mathrm{j}\omega\tau},$$

where ε_s is the static value, ε_∞ the high-frequency (optical) value, and τ is the characteristic relaxation time. The real part corresponds to ε_r', and the imaginary one is a part of the loss factor ε_r'' together with conductivity γ.

An example of the frequency dependence of ε_r' and ε_r'' for water and ice is shown in **Figure 1**. The value drops from the initial value ε_s to the optical level ε_∞ after the relaxation process. E.g., for water, at low frequencies $\varepsilon_r' \approx 81$, but in the optical band $\varepsilon_r' \approx 1.77$. In the interval around the relaxation frequency, the value of the loss factor ε_r'' significantly increases (dashed line in the figure). The relaxation frequency of pure water is approximately 10 GHz. For water bound in tissues, the frequency of the maximum loss factor is lower. Therefore, EM wave with a frequency of 2.45 GHz uses the microwave oven for the most efficient heating of food.

In **Table 1**, there are some typical values of the conductivity of selected tissues for different frequencies. We see that the conductivity at low frequencies is of the order of 0.01–1.00 S m^{-1} (except for dry skin) and increases significantly with the frequency above 1 GHz.

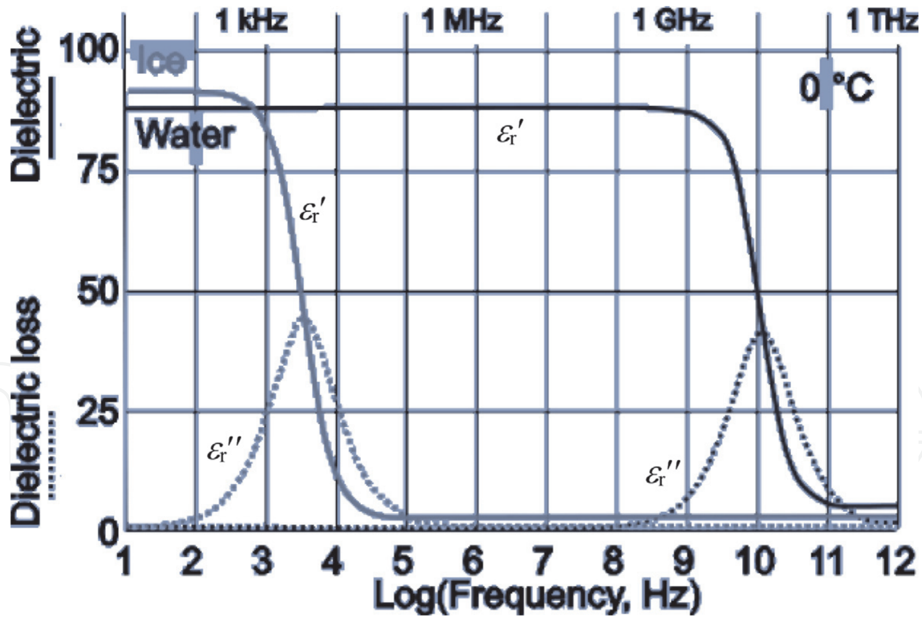

Figure 1.
Frequency dependence of components of complex relative permittivity (source: http://www1.lsbu.ac.uk/water/microwave_water.html).

	Tissue conductivity at different frequencies γ/(S/m)				
	100 Hz	**100 kHz**	**10 MHz**	**1 GHz**	**100 GHz**
Blood	0.700	0.70	1.10	1.58	63.4
Brain	0.109	0.154	0.378	1.31	48.2
Nerve	0.0280	0.0808	0.223	0.600	30.9
Liver	0.0381	0.0846	0.317	0.897	42.9
Lungs inhaled	0.0730	0.107	0.225	0.474	21.4
Kidney	0.102	0.171	0.508	1.45	57.1
Muscles	0.267	0.362	0.617	0.978	62.5
Tendons	0.305	0,389	0.408	0.760	34.9
Fat	0.0406	0.0434	0.0526	0,116	10.6
Bone cortical	0.0201	0.0208	0.0428	12.4	8.66
Dry skin	2.00×10^{-4}	4.51×10^{-4}	0.197	0.900	39.4
Water	2.30×10^{-15}	2.30×10^{-9}	2.30×10^{-5}	0.229	84.4

Table 1.
Tissue conductivity (https://www.itis.ethz.ch/virtual-population/tissue-properties/database/dielectric-properties/).

Tissues with a high content of water are not typical dielectrics. As you see in **Table 2**, the low-frequency relative permittivity is very high, of the order up to10^6. After the first relaxation around 1 MHz, it decreases to the values of the order of 10^1 to 10^2 and then above 10 GHz to values of the order of units. High values at low frequencies cause organic components (macromolecules) in the tissue, which contribute only a little to the alternating polarization at high frequencies.

Knowledge of these values is important for various applications, e.g., diathermy at frequencies of tens of MHz or hyperthermia at frequencies above 1 GHz.

	Relative permittivity at different frequencies $\varepsilon_r'/(-)$				
	100 Hz	**100 kHz**	**10 MHz**	**1 GHz**	**100 GHz**
Blood	5.26×10^3	5.12×10^3	280	61.1	8.30
Brain	3.91×10^6	3.52×10^3	465	48.9	7.38
Nerve	4.66×10^5	5.13×10^3	155	32.3	6.18
Liver	6.78×10^5	7.50×10^3	223	46.4	6.87
Lungs inhaled	1.77×10^6	2.58×10^3	124	21.8	4.00
Kidney	3.52×10^6	7.65×10^3	371	57.9	8.04
Muscles	9.33×10^6	8.09×10^3	171	54.8	8.63
Tendons	1.19×10^7	472	103	45.6	5.98
Fat	1.52×10^5	101	29.6	11.3	3.67
Bone cortical	5.85×10^3	228	36.8	0.156	3.30
Dry skin	1.14×10^3	1.12×10^3	362	40.9	5.6
Water	84.6	84.6	84.6	84.4	8.48

Table 2.
Relative permittivity of tissues.

Example 3. At the frequency of 100 MHz, the muscle parameters are γ = 0.708 S m^{-1}, ε_r = 66, and μ_r = 1.00. The value $\omega\,\varepsilon$ = 0.367 S m^{-1}, which is comparable with the value of γ. For the calculation, we use formulas (28) and (29). After substitution, we have $\beta \approx 3.93$ m^{-1}, $\alpha \approx 21.4$ m^{-1}. From here we get an effective EM wave propagation length of $\delta \approx 25$ cm, a phase velocity of 2.94×10^7 m s^{-1}, and a wavelength of $\lambda \approx 29$ cm.

Thus, most of the energy of EM radiation is absorbed in the tissue in a layer with a depth of approximately $\delta/2 \approx 12.5$ cm.

1.1.2.5 Wave impedance

A quantity, important especially in the transition of waves from one medium to another, is the wave impedance **Z** of the medium, which is the ratio of the phasors of the electric intensity **E** and the magnetic intensity **H**.

From Maxwell's equations for the planar EM wave, which propagates in the direction of the axis z, see equations (14), we obtain the relation for the wave impedance of a direct harmonic wave

$$-\mathbf{k}\ \mathbf{E}^{+}(z,t) = -\mathrm{j}\,\omega\mu\ \mathbf{H}^{+}(z,t) \tag{35}$$

from where

$$\mathbf{Z} = \frac{\mathbf{E}_\mathrm{m}^{+}}{\mathbf{H}_\mathrm{m}^{+}} = \frac{\omega\mu}{\mathbf{k}} = \sqrt{\frac{\mathrm{j}\,\omega\mu}{\gamma + \mathrm{j}\,\omega\varepsilon}}. \tag{36}$$

Z is the *complex wave impedance* of the medium.

For the back wave, we get similarly

$$\mathbf{Z} = -\frac{\mathbf{E}_\mathrm{m}^{-}}{\mathbf{H}_\mathrm{m}^{-}}. \tag{37}$$

The complex wave impedance is a complex number.

$$\mathbf{Z} = Z\ \ \mathrm{e}^{\mathrm{j}\varphi}, \text{where } Z = \frac{E_\mathrm{m}}{H_\mathrm{m}} = \sqrt{\frac{\omega\mu}{\sqrt{\gamma^2 + (\omega\varepsilon)^2}}}, \text{ and } \varphi = \frac{\pi}{4} - \frac{1}{2}\ \ \arctan\frac{\omega\varepsilon}{\gamma}. \tag{38}$$

The absolute value Z of the complex impedance indicates the ratio of the amplitudes of the electric field intensity and the magnetic field intensity. The argument φ of the complex impedance represents the phase shift of the electric field intensity wave function relative to the magnetic field intensity.

For low loss medium $\gamma \ll \omega\ \varepsilon$ (dielectrics).

$$Z \approx \sqrt{\frac{\mu}{\varepsilon}}, \text{ and } \qquad \varphi \approx 0. \tag{39}$$

For high-conductivity medium $\gamma \gg \omega\ \varepsilon$ (conductor).

$$Z \approx \sqrt{\frac{\omega\mu}{\gamma}}, \text{ and } \varphi \approx \pi/4 \text{ rad} = 45°. \tag{40}$$

Example 4. Wave impedance of selected materials.

Vacuum wave impedance $Z_0 = \sqrt{\mu_0/\varepsilon_0} \approx 377\ \Omega$ is practically the wave impedance of air. The dielectric wave impedance ($\gamma \approx 0$ and μ_r = 1) is a real quantity, e.g., distilled, and deionized water is a non-conductor with a permittivity ε_r = 81 in the radiofrequency range. The wave impedance is Z = $Z_0/\sqrt{\varepsilon_r} \approx 42\ \Omega$. For glass with a relative permittivity $\varepsilon_\mathrm{r} \approx 7.6$ for the order of magnitudes, $Z \approx 137\ \Omega$), but with a refractive index n = 1.7 for light, Z = 222 Ω. The wave impedance of copper (γ = 56 MS m^{-1}, μ_r = 1), for which ωε < < γ holds, has an absolute value $Z \approx 1.2$ mΩ for the frequency f = 10 MHz, while the real value $R \approx 0.84$ mΩ is the same size as the imaginary part. The conductor surface is inductive for EM wave.

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1.2 Power transmitted by electromagnetic waves

Electromagnetic waves also transmit power, which causes, e.g., heating the surface of the body, or a mechanical effect on the body on which the wave incidents. It utilizes hyperthermia, laser scalpel, laser lithotripsy, photoacoustic tomography, and the like. Also, visual perception is proportional to the power of light.

If an electric current flow through the medium, work takes place. The electric power density p is the scalar product $p = \boldsymbol{J} \times \boldsymbol{E}$ of the current density and electric field intensity. If we express the current density by Eq. (3), we get

$$p = \mathbf{E} \cdot \left(\mathbf{curl}\,\mathbf{H} - \frac{\partial\mathbf{D}}{\partial t}\right) = -\mathrm{div}\,(\mathbf{E} \times \mathbf{H}) + \mathbf{H} \cdot \mathbf{curl}\,\mathbf{E} - \mathbf{E} \cdot \frac{\partial\mathbf{D}}{\partial t}. \tag{41}$$

Using equation (4) we have

$$\mathbf{E} \cdot \mathbf{J} = -\mathrm{div}\,(\mathbf{E} \times \mathbf{H}) - \mathbf{H} \cdot \frac{\partial \mathbf{B}}{\partial t} - \mathbf{E} \cdot \frac{\partial \mathbf{D}}{\partial t}. \tag{42}$$

If ε and μ do not depend on time, there is

$$\mathbf{H} \cdot \frac{\partial \mathbf{B}}{\partial t} + \mathbf{E} \cdot \frac{\partial \mathbf{D}}{\partial t} = \frac{\partial}{\partial t}\left(\frac{1}{2}\mathbf{H} \cdot \mathbf{B} + \frac{1}{2}\mathbf{E} \cdot \mathbf{D}\right). \tag{43}$$

We can write the power equation in the form

$$-\frac{\partial}{\partial t}\left(\frac{1}{2}\mathbf{H} \cdot \mathbf{B} + \frac{1}{2}\mathbf{E} \cdot \mathbf{D}\right) = \mathbf{E} \cdot \mathbf{J}_0 + \gamma E^2 + \mathrm{div}\,(\mathbf{E} \times \mathbf{H}). \tag{44}$$

The term

$$e_{\mathrm{EM}} = \frac{1}{2}\mathbf{H} \cdot \mathbf{B} + \frac{1}{2}\mathbf{E} \cdot \mathbf{D} \tag{45}$$

represents the energy density of the electromagnetic field.

Eq. (44) describes the energy balance in the volume element of the medium. The left side represents a negative time change (loss) in energy density. The right side reviews the causes of this change. The first term $\boldsymbol{E} \times \boldsymbol{J}_0$ is the power density of the source current $\boldsymbol{J}_0$ and the second $\gamma\, E^{\,2}$ the power dissipation density caused by the medium conductivity. Joule losses cause medium heating and EM wave attenuation. The last term in (44) is a decrease in the energy density of the element due to the irradiation of electromagnetic waves to the surroundings.

If we integrate the equation (44) in volume V of the body, we get

$$-\frac{\mathrm{d}}{\mathrm{d}t}\iiint_V e_{\mathrm{EM}}\,\mathrm{d}V = -P_{\mathrm{source}} + P_{\mathrm{loss}} + \oint\!\!\!\oint_S (\mathbf{E} \times \mathbf{H}) \cdot \mathbf{dS}, \tag{46}$$

where S is the surface that enclose the volume V.

The quantity

$$\mathbf{\Pi} = \mathbf{E} \times \mathbf{H} \tag{47}$$

is called the Poynting vector and represents the areal power density of EM radiation. The radiation power passing through the surface S (radiation power) is

$$P_{\mathrm{rad}} = \iint_S \mathbf{\Pi} \cdot \mathbf{dS}. \tag{48}$$

Mean value of the Poynting vector

$$I = \langle |\mathbf{E} \times \mathbf{H}| \rangle \tag{49}$$

represents the *intensity of radiation*. It is expressed in W m^{-2} units.

In the case of harmonic waves, the intensity of radiation

$$I = E_{\mathrm{m}} H_{\mathrm{m}} \ \cos\varphi \ \left\langle \cos^2 \omega t \right\rangle = \frac{1}{2} E_{\mathrm{m}} H_{\mathrm{m}} \ \cos\varphi = EH \ \cos\varphi, \tag{50}$$

where φ is the phase shift between the phasors **E** and **H** and E, H are the RMS values.

1.3 Transmission of EM waves between two media

When the wave propagates through different spatial structures, various phenomena such as reflection, scattering, interference, diffraction, and the like occur. These phenomena can be both desirable and undesirable. The reflection utilizes, e.g., mirror. The mirror effect also uses EM shielding. On the other hand, due to the reflection of light from the lens surface, the intensity of the radiation entering the glass and passing the lens decreases, and it is, therefore, proper to eliminate the reflection. Waveguides and optical fibers utilize a total reflection of the radiation on the walls. The following paragraphs are devoted to explaining some basic principles and contexts of the mentioned effects.

1.3.1 Reflection and refraction of electromagnetic waves

If the wave incident on the interface of two homogeneous media, there is always a partial reflection from the interface, and a partial crossing of the wave the interface. The phenomena obey the fundamental laws of reflection and refraction, see **Figure 2**.

All three rays, and the normal line (dashed) at the point of impact of the beam to the interface, lie in one plane. If the wave is incident at angle α concerning the normal line to the interface, the angles of reflection α' and refraction β are as follows.

$$\alpha' = \alpha \text{ and } \sin\beta = \frac{c_2}{c_1} \sin\alpha, \text{resp.} \sin\beta = \frac{n_1}{n_2} \sin\alpha. \tag{51}$$

where c_1 and c_2 are the speeds of wave in the individual media, and n_1, n_2 the refractive indices of both media.

1.3.2 Transition of EM waves energy between two media

When assessing the intensity of the wave reflected from the interface and passing through the interface, we will start from the simplifying assumption of the

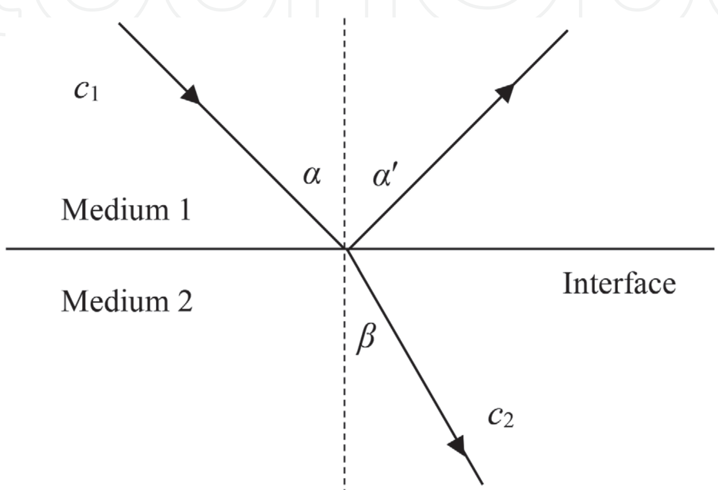

Figure 2.
Reflection and refraction of waves at the interface of two media.

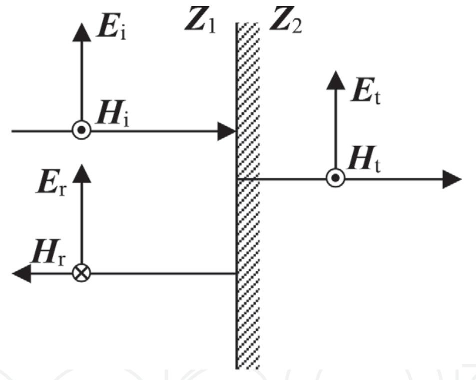

Figure 3.
EM wave transition Prechod EM vlny rozhraním.

perpendicular impact of the harmonic EM wave on the plane interface of two homogeneous environments.

The situation illustrates in **Figure 3**. Indices refer to "i"—incident wave, "t"—transmitted wave, and "r"—reflected wave. The solution of the field at the interface results from the boundary conditions for the EM field. The tangent components of electric and magnetic field intensity are maintained at the interface, i.e.,

$$\mathbf{E}_\mathrm{i} + \mathbf{E}_\mathrm{r} = \mathbf{E}_\mathrm{t}, \tag{52}$$

$$\mathbf{H}_\mathrm{i} + \mathbf{H}_\mathrm{r} = \mathbf{H}_\mathrm{t}, \tag{53}$$

where we have $\mathbf{E}_\mathrm{i} = \mathbf{Z}_1 \mathbf{H}_\mathrm{i}$, $\mathbf{E}_\mathrm{t} = \mathbf{Z}_2 \mathbf{H}_\mathrm{t}$, and $\mathbf{E}_\mathrm{r} = -\mathbf{Z}_1 \mathbf{H}_\mathrm{r}$.

After replacing and adjusting the system of equations, we get relationships.

$$\mathbf{E}_\mathrm{r} = \frac{\mathbf{Z}_2 - \mathbf{Z}_1}{\mathbf{Z}_2 + \mathbf{Z}_1} \ \mathbf{E}_\mathrm{i}, \mathbf{E}_\mathrm{t} = \frac{2\mathbf{Z}_2}{\mathbf{Z}_2 + \mathbf{Z}_1} \ \mathbf{E}_\mathrm{i}, \tag{54}$$

$$\mathbf{H}_\mathrm{r} = -\frac{\mathbf{Z}_2 - \mathbf{Z}_1}{\mathbf{Z}_2 + \mathbf{Z}_1} \ \mathbf{H}_\mathrm{i}, \mathbf{H}_\mathrm{t} = \frac{2\mathbf{Z}_1}{\mathbf{Z}_2 + \mathbf{Z}_1} \ \mathbf{H}_\mathrm{i}. \tag{55}$$

$$I_\mathrm{r} = \left|\frac{\mathbf{Z}_2 - \mathbf{Z}_1}{\mathbf{Z}_2 + \mathbf{Z}_1}\right|^2 \ I_\mathrm{i}, I_\mathrm{t} = \frac{4\,\mathrm{Re}\left\{\mathbf{Z}_2 \mathbf{Z}_1^*\right\}}{\left|\mathbf{Z}_2 + \mathbf{Z}_1\right|^2} \quad I_\mathrm{i}. \tag{56}$$

As a result, we can see that the EM wave impact on any interface of media with different impedances, leads to the reflection of the wave and thus to the loss of intensity of the penetrating wave.

In the case of non-magnetic dielectric substances $\mu_\mathrm{r} = 1$ and $Z = \frac{Z_0}{\sqrt{\varepsilon_\mathrm{r}}} = \frac{Z_0}{n}$,

where $Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}}$ is the wave impedance of vacuum and $n = \sqrt{\varepsilon_\mathrm{r}}$ the refractive index.

The intensity of the reflected and transmitted waves are expressed by means of the refractive indices.

$$I_\mathrm{r} = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2 \ I_\mathrm{i}, \qquad I_\mathrm{t} = \frac{4 n_1 n_2}{(n_2 + n_1)^2} \quad I_\mathrm{i}. \tag{57}$$

Note: Since we have not considered losses, $I_\mathrm{r} + I_\mathrm{t} = I_\mathrm{i}$ is valid, which can be proved by the simple addition of relations (57).

Example 5. Reflection of light from the glass.

When light falls on the optical lens of glasses, telescopes, cameras, etc., some of the light power reflects from the lens surface. Consider the refractive index of glass n_2 = 1.7. Then we get the intensity of reflected and transmitted light for n_1 = 1 (air), $I_r \approx 0.067\, I_i$, and $I_t \approx 0.933\, I_i$. As we see, 6.7% of the incident power reflects from the surface. This intensity is usually enough to see our mirror image in a glass window, especially if the dark background is behind it. An anti-reflective layer (which discusses the next paragraph) is applied to the surface of the glass optical elements to prevent the intensity loss by the reflection.

Example 6. Reflection of EM wave from the conductor surface.

If an EM wave with a frequency of 10 MHz falls from the air onto the aluminum surface (γ = 37 MS m^{-1}, μ_r = 1.0), due to inequality $Z_1 \gg Z_2$, the reflection factor is $I_r/I_i \approx 1$. Transition factor

$$\frac{I_t}{I_i} = \frac{4\,\mathrm{Re}\left\{\mathbf{Z}_2\mathbf{Z}_1^*\right\}}{|\mathbf{Z}_2 + \mathbf{Z}_1|^2} \approx \frac{4\,\mathrm{Re}\,\mathbf{Z}_2}{Z_1} = \frac{4}{Z_0}\sqrt{\frac{\omega\mu_0}{2\gamma}} = 4\sqrt{\frac{\omega\varepsilon_0}{2\gamma}} \approx 1,1 \times 10^{-5}.$$

As a result, we can see that the conductive layer on the body surface almost perfectly shields the internal volume from the external EM field in the radio frequency region. Despite such a small amount of power penetrating the body, we can achieve the demanded surface heating.

For tissue with significantly lower conductivity, the power transfer factor is up to three orders greater (up to 10%). The tissue at higher frequencies is no more a good conductor. The condition $\gamma \gg \omega\,\varepsilon$ at higher frequencies is not valid, and the tissue behaves more like a lossy dielectric.

1.3.3 Transition of EM waves through a dielectric layer

To achieve a higher reflection factor (e.g., reflective UV filters on glasses or cameras), or to reduce the reflectivity (e.g., anti-reflective layers on glasses or lenses), the thin layers are applied to the glass surface.

Consider a set of three media, in which layer 2 is between media 1 and 3, **Figure 4**. There are two interfaces in the system. We are interested in the transition of EM waves through this structure and reflection from the first interface.

Again, we consider a simple case of the perpendicular impact of the harmonic wave with the $\boldsymbol{E}_0$, $\boldsymbol{H}_0$ electric, and magnetic field intensities. Reflected wave r1 propagates back from the first interface. Inside the layer, the resulting wave consists of the direct wave t1 and the reflected one r2. From the second interface, the wave t2 propagates into the third medium.

Boundary conditions apply to the phasors of the EM field quantities at the interfaces.

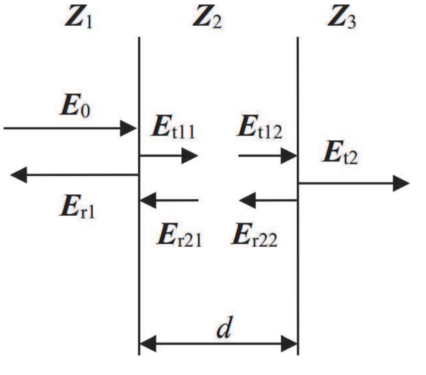

Figure 4.
Transition of an EM through a thin layer.

$$\mathbf{E}_0 + \mathbf{E}_{r1} = \mathbf{E}_{t11}, \quad \mathbf{H}_0 + \mathbf{H}_{r1} = \mathbf{H}_{t11},$$
$$\mathbf{E}_{t12} + \mathbf{E}_{r22} = \mathbf{E}_{t2}, \quad \mathbf{H}_{t12} + \mathbf{H}_{r22} = \mathbf{H}_{t2}, \tag{58}$$

with relationships

$$\mathbf{E}_0 = \mathbf{Z}_1 \mathbf{H}_0, \quad \mathbf{E}_{r1} = -\mathbf{Z}_1 \mathbf{H}_{r1}, \; \mathbf{E}_{t1} = \mathbf{Z}_2 \mathbf{H}_{t1}, \quad \mathbf{E}_{r2} = -\mathbf{Z}_2 \mathbf{H}_{r2}, \quad \mathbf{E}_{t2} = \mathbf{Z}_3 \mathbf{H}_{t3}, \tag{59}$$

and further

$$\mathbf{E}_{t12} = \mathbf{E}_{t11} \; e^{-j\mathbf{k}d}, \quad \mathbf{E}_{r21} = \mathbf{E}_{r22} \; e^{j\mathbf{k}d}, \tag{60}$$

where d is the thickness of the middle layer and $\mathbf{k}$ is the coefficient of wave propagation in it.

From these equations and relations, we get after adjustment the complex factors $\mathbf{r}$ of reflection from the middle layer and $\mathbf{t}$ of the transition through the layer.

$$\mathbf{r} = \frac{\mathbf{E}_{r1}}{\mathbf{E}_0} = \frac{(\mathbf{Z}_2 - \mathbf{Z}_1)(\mathbf{Z}_2 + \mathbf{Z}_3) + (\mathbf{Z}_2 + \mathbf{Z}_1)(\mathbf{Z}_3 - \mathbf{Z}_2)e^{-j2\mathbf{k}d}}{(\mathbf{Z}_2 + \mathbf{Z}_1)(\mathbf{Z}_2 + \mathbf{Z}_3) + (\mathbf{Z}_2 - \mathbf{Z}_1)(\mathbf{Z}_3 - \mathbf{Z}_2)\,e^{-j2\mathbf{k}d}}, \tag{61}$$

$$\mathbf{t} = \frac{\mathbf{E}_{t2}}{\mathbf{E}_0} = \frac{4\mathbf{Z}_3\,\mathbf{Z}_2\,e^{-j\,\mathbf{k}d}}{(\mathbf{Z}_2 + \mathbf{Z}_1)(\mathbf{Z}_2 + \mathbf{Z}_3) + (\mathbf{Z}_2 - \mathbf{Z}_1)(\mathbf{Z}_3 - \mathbf{Z}_2)\,e^{-j2\mathbf{k}d}}. \tag{62}$$

Compare with the same result for acoustic waves (see Chapter 3).

As we can see from these relations, the coefficients $\mathbf{r}$ and $\mathbf{t}$ depend on the thickness d of the middle layer.

To give an idea of the nature of the phenomenon, let us analyze the case of lossless dielectric and non-magnetic media with real impedance and wavenumber values.

$$Z_i = \frac{Z_0}{\sqrt{\varepsilon_{ri}}} = \frac{Z_0}{n_i}, \text{for } i = 1, 2, 3, \text{and } k = \frac{\omega}{c_0} \; \sqrt{\varepsilon_{r2}} = \frac{\omega}{c_0} \; n_2,$$

where Z_0, c_0 are vacuum impedance and EM wave speed in a vacuum.

Taking these relations into account, we adjust equations (61), (62) to form

$$\mathbf{r} = \frac{\mathbf{E}_{r1}}{\mathbf{E}_0} = \frac{(n_1 - n_2)(n_2 + n_3) + (n_1 + n_2)(n_2 - n_3)e^{-j2kd}}{(n_1 + n_2)(n_2 + n_3) + (n_1 - n_2)(n_2 - n_3)\,e^{-j2kd}}, \tag{63}$$

$$\mathbf{t} = \frac{\mathbf{E}_{t2}}{\mathbf{E}_0} = \frac{4n_1 n_2\,e^{-jkd}}{(n_1 + n_2)(n_3 + n_2) + (n_1 - n_2)(n_2 - n_3)\,e^{-j2kd}}. \tag{64}$$

We express the intensity of radiation for individual media $I = E^2/Z$ and determine the rates of reflected and transmitted wave intensities

$$\frac{I_{r1}}{I_0} = \frac{[(n_1 - n_2)(n_2 + n_3) + (n_1 + n_2)(n_2 - n_3)\,\cos 2kd]^2 + \; [(n_1 + n_2)(n_2 - n_3)\,\sin 2kd]^2}{[(n_1 + n_2)(n_2 + n_3) + (n_1 - n_2)(n_2 - n_3)\,\cos 2kd]^2 + [(n_1 - n_2)(n_2 - n_3)\,\sin 2kd]^2}, \tag{65}$$

$$\frac{I_{t2}}{I_0} = \frac{16\,n_1 n_2^2\,n_3}{[(n_1 + n_2)(n_3 + n_2) + (n_1 - n_2)(n_2 - n_3)\,\cos 2kd]^2 + [(n_1 - n_2)(n_2 - n_3)\,\sin 2kd]^2}. \tag{66}$$

The graph of the reflection and transmission factors is in **Figure 5** for $n_1 = 1.00$ (air), $n_2 = 1.40$ (layer), and $n_3 = 1.90$ (glass). The graph shows that if $k\,d = \pi/2$ rad,

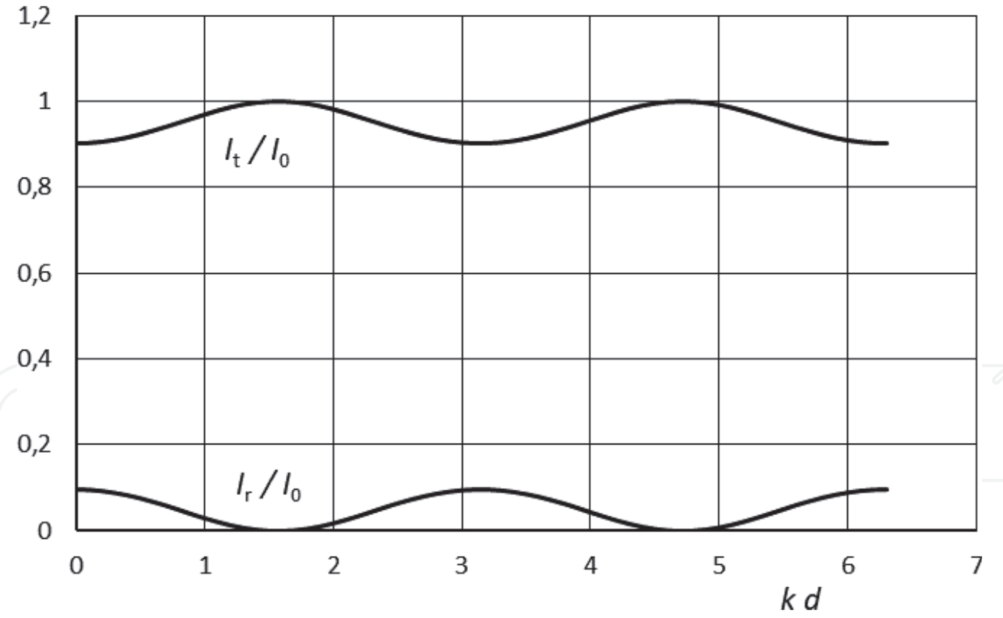

Figure 5.
Graf of reflection and intensity transition factors versus wave thickness k d (n_1 = 1.00, n_2 = 1.40, n_3 = 1.90).

i.e., $d = \lambda/4$, is zero reflection and 100% transition. It represents an anti-reflective layer (e.g., on reading glasses). On the other hand, for the $k\,d = \pi$ rad, the reflection is maximum (reflective layer as a UV filter on sunglasses). Thin layers on the optical elements (*antireflective or reflective*) control the reflection of light from their surfaces. The condition of zero reflection, resp. maximum reflection is fulfilled only for one wavelength, i.e., light color. In practice, antireflective layers are composed of several layers of different materials placed successively on each other.

1.4 Quantum properties of EM waves

At the beginning of the twentieth century, the quantum nature of EM radiation was discovered. According to quantum theory, radiation generates in elementary quanta—*photons* that have properties as the classical particles. Similarly, in the interaction of EM radiation with the structure of the substance, radiation is also absorbed in these quanta. Quantum theory explains the nature of spectra of the bodies' thermal radiation, the external photoelectric effect, the optical properties of substances, the electrical conductivity of semiconductors, and many other phenomena.

Electromagnetic radiation has two forms of manifestation. In some contexts, it behaves like a wave with frequency f and wavelength λ (wave parameters), in other ones, like a flow of particles (photons) with energy E_{ph} and momentum p_{ph} (mechanical parameters). The relations between wave and particle parameters describe de Broglie equations.

$$E_{ph} = h\ f, \text{and}\, p_{ph} = \frac{h}{\lambda}, \tag{67}$$

where h is the Planck′s constant.

At the Sun's surface temperature T = 5780 K, the Sun most intensively radiates light with a wavelength $\lambda \approx 500$ nm, which corresponds to a photon energy $E_{ph} \approx 2.1$ eV ($\approx 4.0 \times 10^{-19}$ J) and a yellow-green color. To this color, the human eye is most sensitive.

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Spatially confined structures (atoms, molecules, crystals, etc.) have discrete energy levels of stationary states, e.g., electrons in atoms have only specific values of energy. If the system is in a state with energy E_1, it can go into a state with energy $E_2 > E_1$ (excitation) due to the absorption of a photon of the radiation with energy $E_{ph} = E_2 - E_1$. If the system is excited with the energy E_2, it spontaneously returns to a lower state with energy $E_1 < E_2$ (relaxation). The energy difference $\Delta E = E_2 - E_1$ is usually released in the form of a photon. This results in the *emission of a photon* (radiation) with a wavelength

$$\lambda = \frac{h\,c}{E_2 - E_1}. \tag{68}$$

When EM radiation passes through a certain substance, it absorbs the photons with energy corresponding to the transitions between its energy levels. The corresponding wavelengths will miss in the transmitted radiation. It results in *the absorption spectrum* of the substance. On the other hand, if we excite the substance, e.g., by electric discharge, the system relaxes to the lower state and emits photons of corresponding transition energies. Thus, the radiation contains only radiation with certain characteristic wavelengths. In such a way arises the *emission spectrum* of the substance. The emission or absorption spectrum is typical for any substance. This phenomenon is a base of *emission or absorption spectroscopy*. In medicine, *optical spectroscopy* is useful for biochemical analyses and in hematology. Another tool of biomedicine is magnetic resonance spectroscopy.

Each system has its characteristic values of binding energy E_b (energy for separation of some part of the system or the overall disintegration of the system into elementary parts). If a photon with the energy $E_{ph} \geq E_b$ enters the system, it may cause its dissociation (decay). E.g., if an atom or group of atoms belonging to the DNA macromolecule with the binding energy E_b, the EM radiation with the wavelength $\lambda \leq h\,c/E_b$ can break the binding and release some of its parts. Such a damaged DNA molecule may originate a tumor formation. Since the binding energies of molecules reach values of several eV (electron-volts), the corresponding wavelengths of radiation are several hundred nm. It corresponds to the ultraviolet radiation, e.g., for $E_b \sim 4$ eV, the wavelength $\lambda \sim 310$ nm (ultraviolet UVB band). The O_2 molecule has a binding energy of 5.1 eV, so that if the radiation with a wavelength $\lambda < 244$ nm (UVC band) irradiates, the dissociation of the molecules results in arising of one atomic oxygen. The free O atoms then bind to the O_2 molecules and form O_3 molecules (ozone). In such a way, solar ultraviolet UVC radiation absorbs in the upper atmosphere and creates the ozonosphere.

Electrons in atoms and molecules are bound by binding energy, which calls *ionizing energy*. The substance with ionizing energy E_i ionizes when exposed to radiation with a wavelength $\lambda \leq h\,c/E_i$. For the oxygen and nitrogen binding energies E_i (O_2) = 13.6 eV and E_i (N_2) = 14.5 eV, air ionization occurs, if EM wavelengths $\lambda < 90$ nm. Due to the far UV and X radiation from the sun, the highest atmospheric layer ionizes, creating an ionosphere.

In such a way atmosphere protects the surface of the Earth against the dangerous short-wavelengths radiation from the Sun.

From the above examples, we see that the interface between ionizing and non-ionizing EM radiation is approximately the wavelength of about 100 nm and the corresponding photon energy about 12 eV.

The photon energies of the EM radiation in the different bands of EM radiation are given in the last column in **Table 3**.

Band	Wavelength λ (approx.)	Frequency f (approx.)	Photon energy E_{ph} (approx.)
Very long waves	>1 km	<300 kHz	<1 neV
Radio waves (RF)	1 km–1 m	300 kHz–300 MHz	1 neV–1 μeV
Microwaves (MW)	1 m–1 mm	300 MHz–300 GHz	1 μeV–1 meV
Infrared radiation (IR)	1 mm–700 nm	300 GHz–430 THz	1 meV–1.8 eV
Visible light (VL)	700–400 nm	430–750 THz	1.8–3.1 eV
Ultraviolet radiation (UV)	400–100 nm	750 THz–3 PHz	3.1–12 eV
Edge of ionizing radiation	100 nm	3 PHz = $3{\cdot}10^{15}$ Hz	12 eV
Extreme ultraviolet radiation (EUV)	100–10 nm	$3{\cdot}10^{15}$–$3{\cdot}10^{16}$ Hz	12–100 eV
Roentgen radiation (X)	10 nm–1 pm	$3{\cdot}10^{16}$–$3{\cdot}10^{20}$ Hz	100 eV–1 MeV
Gamma radiation (γ)	1 pm–1 fm	$3{\cdot}10^{20}$–$3{\cdot}10^{23}$ Hz	1 MeV–10 GeV
High-energy gamma rays	<1 fm	>$3{\cdot}10^{23}$ Hz	>10 GeV

Table 3.
Characteristic bands of electromagnetic waves. The boundaries of the bands are only approximate, the wavelength is calculated for the vacuum, where $\lambda = c_o/f$, *photon energy* $E_{ph} = h\,f$.

1.5 Spectrum of EM waves

Although the nature of EM waves is the same for all frequencies, the characteristics, effects of EM waves, and practical applications vary across different frequency bands. **Table 3** shows the classic distribution.

Very long waves up to a wavelength equal to the length of the Earth's perimeter occur in nature, caused by, e.g., atmospheric discharges (lightning), affecting living organisms as a part of the environment. We can mention, e.g., Schumann resonances, which correspond to a wavelength $\lambda = 2\,\pi\,R_z \approx 40{,}000$ km, and a frequency of 7.5 Hz, which falls within the range of the human brain waves frequency. It is known that this EM field mainly affects the mental side of the man and affects his immune system. This is used in some forms of therapy at very low-frequency waves, which produce some animals (e.g., dogs—*Canis therapy*, horses—*hippotherapy*, cats—*feline therapy*, *dolphin therapy*, etc.)

Radio-frequency waves (*RF*) are used mainly in the transmission of radio and television signals, radiolocation, electromagnetic flaw detection, surface heating of conductive materials, etc. In medicine, RF waves also use magnetic resonance imaging and diathermy. Research is underway to investigate the effects of the radiofrequency EM field on biological systems with a prognosis of cancer treatment.

Microwaves (*MW*) are used in transmitting signals on the direct visibility, or in waveguides, satellite communication, mobile communication, radiolocation, microwave heating, in medicine, especially in hyperthermia and tumor treatment.

Infrared radiation (*IR*) is typical for radiant heat transfer. It is used for signal transmission by optical fibers, measuring the surface temperature of bodies, in medicine, especially for diagnostics by the method of thermography. IR laser radiation uses laser scalpels and lithotripsy, or IR spectroscopy (oximetry, photoplethysmography, e.g., Borik and Cap [4], measurement of blood flow), etc.

Visible light (*VL*) is the dominant information channel of a human being and is used in various optical devices such as binoculars, microscopes, magnifying glasses, glasses, lighting tools, etc. In medicine, light use, also, optical imaging and lighting in surgery, phototherapy, endoscopy, and the like. Different light attenuation or light dispersion in substances at different wavelengths uses optical spectroscopy of biological materials, photoplethysmography Borik et al. [5], Borik and Cap [4, 6], Blazek et al. [7], ophthalmic surgery using optical lasers, etc.

Ultraviolet radiation (*UV*) reaches the limit of ionizing radiation (wavelength of approximately 100 nm). According to the wavelength, the UV band is divided into three parts: UVA (400–320) nm, UVB (320–280) nm, and UVC (280–100) nm. UVA radiation has greater penetration depth than light. It uses, e.g., dermatology. The UVA component of the Sun's radiation disperses in the atmosphere and reaches the Earth's surface (like light). UVB takes place in the production of vitamin D. Its greater exposure leads to erythema (skin inflammation) and pigmentation during tanning. The ozone layer reduces the UVB component of the sun. Its intensity significantly increases with altitude, and therefore tanning is dangerous at the high mountains. UVC has a profound effect on chemical bonds. It can cause skin cancer and has a significant disinfectant effect due to destroying microorganisms. The UVC component of the sun's radiation is attenuated by the atmosphere so that it practically does not reach the earth's surface. UVC and UVB contribute to the formation of the ozone layer of the Earth's atmosphere, which protects the biosphere at the earth's surface from the effects of UVC, EUV, and the X-rays from the Sun. UV radiation harms human vision and leads to damage of the retina at a greater intensity. Because the retina of the eye is not sensitive to UV radiation, it does not have a reflexive protective narrowing of the pupil. The retina is thus exposed to high radiation intensity, and therefore quality sunglasses contain a UV filter.

The edge of ionizing radiation is derived from photon energy, at which the ionization of air molecules begins to take place. The edge is for reference only. Ionization processes and disruption of chemical bonds can also occur in the energy field below this threshold.

Extreme Ultraviolet radiation (*EUV*) or far ultraviolet radiation causes ionizing effects and modification of chemical bonds. On the Earth, it originates only from artificial sources. The EUV and X components of solar radiation are trapped in the upper atmosphere (ionosphere) and do not reach the earth's surface.

X-rays are ionizing radiation, which has a high penetration depth. It penetrates through the entire volume of the human body. In technical practice, it uses mainly body electromagnetic testing. In medicine, it is used mainly in radiology from classical X-rays devices to modern CT imaging, **Figure 6**, Röntgen [8]. Due to the destructive effect of X-rays on biological tissue, it uses radiotherapy of tumors and various bone growths. Due to damage to biological structures, the human organism can be safely exposed only to limited doses of radiation determined by hygiene standards.

Gamma radiation is a very penetrating ionizing radiation that is generated by nuclei of atoms (nuclear radiation). It uses *nuclear medicine*. Weak radiation doses utilize diagnostic devices such as gamma camera, PET (Positron Emission Tomography), and SPECT (Single Photon Emission Tomography); often used radioactive radiators are preparations: cobalt ^{60}Co, cesium ^{133}Cs, iridium ^{192}Ir, and others. Modern nuclear therapy facilities include *Leksell's gamma knife* or, less common *cyber-knife*.

High-energy gamma radiation is EM radiation with a wavelength of less than 10^{-15} m. This radiation with photon energy above 10 GeV arises in huge particle accelerators that serve scientific purposes. Before, this radiation was called *cosmic radiation*, because of its origin in cosmic space.

Maxwell's EM field theory is useful for the classical description of EM radiation, which emphasizes its wave character. EM waves characterize wave-quantities as the

Figure 6.
X-rays image of the hand, Wilhelm Conrad roentgen (1845–1923).

angular frequency ω and wave vector $\boldsymbol{k}$, as described in the previous sections. The components of the wave vector β and α or phase velocity c describe the propagation of EM waves in the medium. The damping coefficient β and the phase shift coefficient α depend on the frequency of the EM wave through the frequency dependence of the quantities μ, ε, and γ.

An example is a seawater, which has a high conductivity $\gamma \sim 1$ S/m. At radio-frequency $f = 10$ MHz, the permittivity of water is $\varepsilon_r \approx 81$. The relation $\omega \varepsilon \approx 4.4 \times 10^{-2}$ S/m $\ll \gamma$ is valid. It is, therefore, a well-conducting medium for which the penetrating depth $\delta \approx 16$ cm. For the visible light, $\delta \sim 10$ m (and transparency up to 200 m) is given for clean seawater. It is known that radio communication is not possible with submarines, while optical visibility is very good in pure seawater. Another example is a soft tissue that is opaque for the visible light but permeable for X-rays. In some cases, quantum processes influence the frequency dependence of the attenuation coefficient β. E.g., the Ge semiconductor monocrystal is transparent (like glass) for wavelengths $\lambda > 1.7$ μm, while for shorter wavelengths $\lambda < 1.7$ μm the Ge monocrystal is opaque (looks like shiny metal). It uses infrared optics in thermographic cameras.

The relatively low attenuation of X-rays in substances is used in medical diagnostics. X-rays have been used in medicine practically since the discovery of X-rays in 1895.

Imaging the internal structure of the body uses different attenuation of X-rays in different tissues, **Figure 6**. The original direct method—*skiascopy (gr. skias—shadow)*, uses the detection of radiation penetrating the body on the screen of the device. The more complex CT (Computed Tomography) method uses the detection of passing X-rays by a series of detectors and computer signal processing. As this is ionizing radiation, human exposition must be kept to a minimum under hygiene standards.

1.6 Sources of electromagnetic radiation

EM radiation sources have a very diverse character, which depends on the wavelength of the generated radiation. The diversity of resources also depends on the purpose of their use. We divide the sources into three groups according to the dominance of the manifestation of the generated radiation:

- sources of coherent waves.
- sources of energy radiation.
- photon radiation sources (dominated by quantum behavior).

The same EM radiation can occur in all three groups according to its further use, e.g., in the case of light, its wave properties can be used in the event of interference; a focused light beam can induce a thermal (energetic) effect, e.g., laser scalpel, or light can be used in typically quantum phenomena such as photoemission of electrons from a metal surface or optical spectroscopy.

1.6.1 Coherent and incoherent resources

If EM radiation behaves like waves, the wave sources are *coherent (coherent = interrelated*) or *incoherent*. Two waves are coherent if they have the same frequency and have a constant phase difference at any point in the space. The coherent source generates a wave with a constant initial phase so that the wave function is unambiguously defined. A coherent source is, e.g., a radio wave antenna supplied by a harmonic voltage source. The optical coherent source is, e.g., LASER, which achieves coherence using a wave resonator. The waves (sources) in which the phase relationship is not defined, are *incoherent*. Many microscopic sources, not mutually coordinated, generate such radiation, e.g., the individual atoms in the filament lamps generate light with a minimally coordinated phase. Incoherent sources are heat sources, noise sources, light bulbs, discharge lamps, LEDs, sources of X-rays, gamma radiation, etc.

Note: A coherent source can be created from an incoherent optical source using a resonator—e.g., incoherent LED source + resonator → coherent semiconductor LASER.

Incoherent sources emit EM radiation usually in elementary "wavelets". A wavelet itself is coherent, but the different wavelets are incoherent. Each radiation has several periods, in space several wavelengths, of coherence. The *coherence length* is the propagation distance in which the radiation is coherent. Coherence is important in the interference processes. If the phase relationships are random, no interference occurs. In the case of interference, diffraction, or holography, phase relationships are decisive. For such cases, we assess the necessary coherence of radiation by comparing the coherence length with characteristic dimensions of the structure on which interference or diffraction arises.

Waves of radiofrequency sources have the coherence length up to thousands of kilometers, of the LASER hundreds of meters. On the other hand, thermal radiation, e.g., a bulb light, radiation of electric discharge, or radiation of LEDs reaches the coherence length of less than a tenth of a millimeter. X-rays of most sources have a coherence length of the magnitude order comparable to the interatomic distances in substances, gamma rays of the magnitude order comparable to the dimensions of the atomic nucleus.

The particles, e.g., electrons, neutrons, protons, ions, also behave like a wave. In such a case, the coherence is understood differently, and quantum mechanics gives the answers. The wave behavior is also observed when a single particle interacts with a fabric structure if the wavelength of the de Broglie wave is comparable to or greater than the characteristic dimensions of the structure with which the particles interact. This fact is used, e.g., in the electron microscope.

1.6.2 Sources of radiofrequency and microwave EM waves

Conductors with non-stationary electric current generate EM waves. Their sources—*antennas* are essentially oscillating electric or magnetic dipoles. An

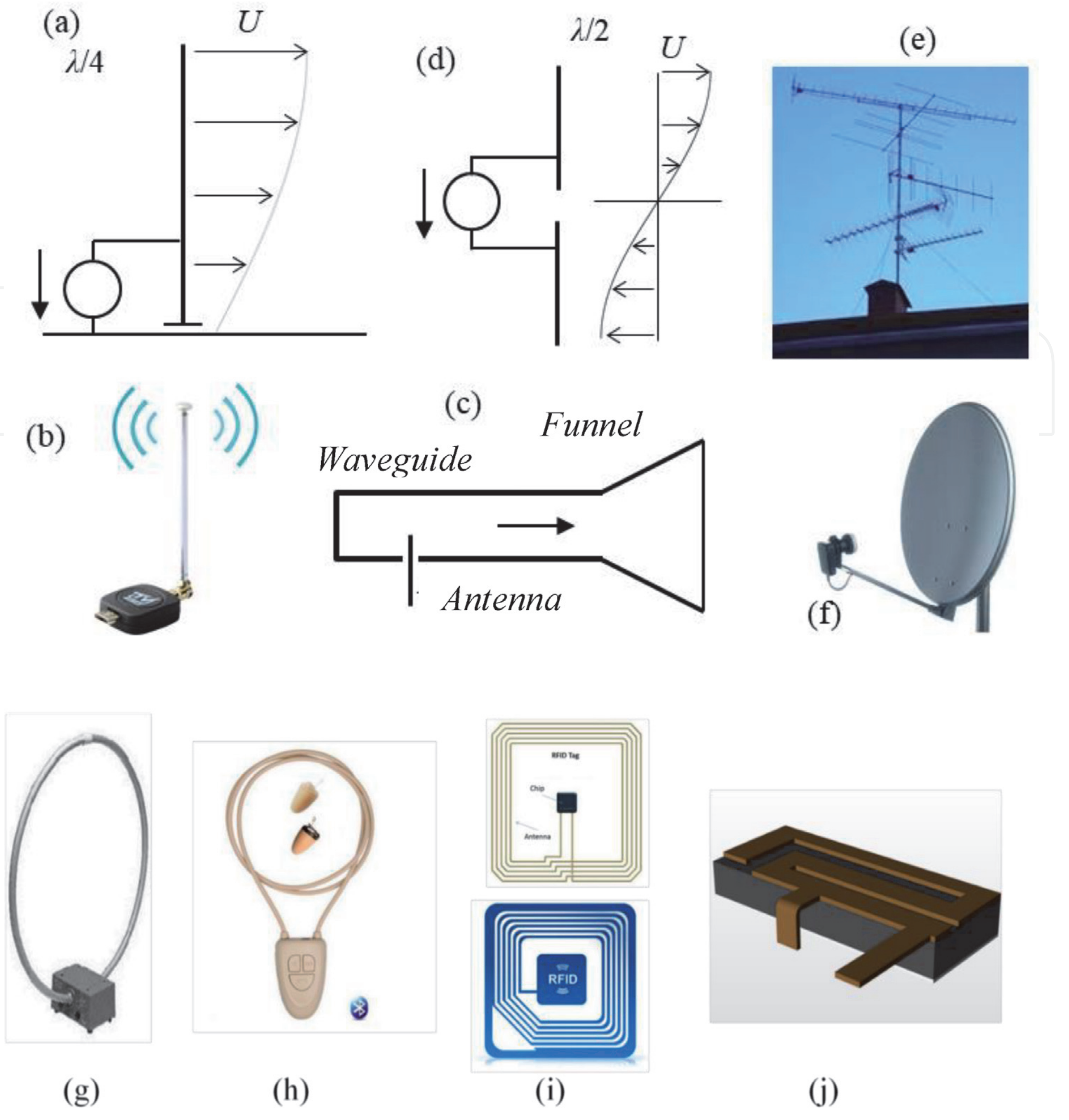

Figure 7.
EM waves antennas.

example of electric dipole antennas for radio and microwave radiation is in **Figure 7**. Figure (a) shows a quarter-wave antenna with the indicated voltage wave distribution. One of its ends is grounded (level of zero potential). Radio transmission on long, medium, and short waves, or short-distance transmission systems (e.g., WIFI—figure (b)), use such antennas. In figure (c) is the dipole antenna for the generation of EM waves in a waveguide. In figure (d) is a half-wave antenna (dipole) with an indicated voltage distribution. Half-wavelength antennas of this type of use wave transmission in VHF and UHF bands (radio, TV, telecommunications), see figure (e). The directivity and thus the gain of the antennas adjust various elements.

The so-called Yagi antenna is in figure (e). Its directionality is adjusted by other elements, in front of and behind the radiating dipole. The directionality of EM wave emission from the waveguide, figure (c), is achieved by a funnel-shaped extension of the waveguide.

The parabolic mirror, figure (f), also serves to form a very narrow radiating characteristic. In this case, the little dipole radiator is placed in the focal plane of the parabolic dish. Satellite communication antennas narrowly directed telecommunication connections, systems of microwave data transmission, etc., use this type of antenna. Some antennas also use a current excitation. They have the shape of loops or coils. The typical loop antenna is in figure (g). The bluetooth connection uses the loop antenna in figure (h). RFID (Radio Frequency Identification) technology uses an antenna in figure (i). It appears, e.g., as security elements of goods, or a smart card identification element. Special planar antennas PIFA (Planar Inverted F-Antennas) with small dimensions, figure (j), is proper for mobile devices, e.g., mobile phones.

1.6.3 Sources of incoherent optical radiation

Incoherent optical sources, which include sources of visible light, infrared, ultraviolet, and X-rays, are divided into temperature sources and quantum sources with spontaneous relaxation.

The principle of the action of these sources relates to photon emission, which accompanies spontaneous transitions of electrons from higher energy states to lower ones. These spontaneous transitions are coherent around the relaxing atom only in a small volume with dimensions of the order of units of the wavelength. The coherence length is, therefore, very small. In the optical region, it is of the order of magnitude of units to tens of micrometers.

Note: Interference phenomena, such as grating diffraction or thin-film interference, occur only if the coherence length is greater than the characteristic dimension of the structure (grating constant, layer thickness, etc.). On the thin oil layer on the surface of the flour, we see color effects if the layer is thin. If it is thicker, it has the appearance of a gray mirror. Since the coherence length of the sunlight is several times its wavelength, it is possible to decompose the light into spectral components by an optical grating. However, this coherence length is not enough to create a hologram.

In the case of substances with electron energy bands, there are many possibilities for a relaxation transition, and the emitted radiation has a wide continuous spectrum. In the case of individual atoms (e.g., gas discharge lamps) with discrete energy levels, the spectrum of the emitted radiation is a discrete one, as well.

1.6.3.1 Heat sources, filament lamps, and arc lamps

Thermal radiation is emitted from the surface of the body in a state of thermodynamic equilibrium. If the thermodynamic temperature of the body surface is T, the spectral composition of the radiation emitted from the body surface gets Planck's law

$$I(\lambda) = \frac{\mathrm{d}I_\lambda}{\mathrm{d}\lambda} = \frac{2\pi h c^2}{\lambda^5} \; \frac{1}{\mathrm{e}^{\frac{hc}{\lambda k_\mathrm{B} T}} - 1} \;, \tag{69}$$

where $I(\lambda)$ is the spectral density of the radiation. A characteristic property of temperature sources is their continuous frequency spectrum (*polychromatic sources*).

The graph of the spectral density $I(\lambda)$ vs. the wavelength λ is in **Figure 8**. In the picture on the left, we see the spectrum of the Sun's radiation (6000 K) compared to a filament lamp (3000 K). The picture on the right shows the radiation spectrum of the human body surface (37 ± 2°C), which is used in thermography and in the non-contact measurement of body temperature. As can be seen from the figures, the maximum spectral density of the radiation intensity is approximately 500 nm (yellow-green color) for solar radiation and about 9–10 μm (infrared radiation) for the human body.

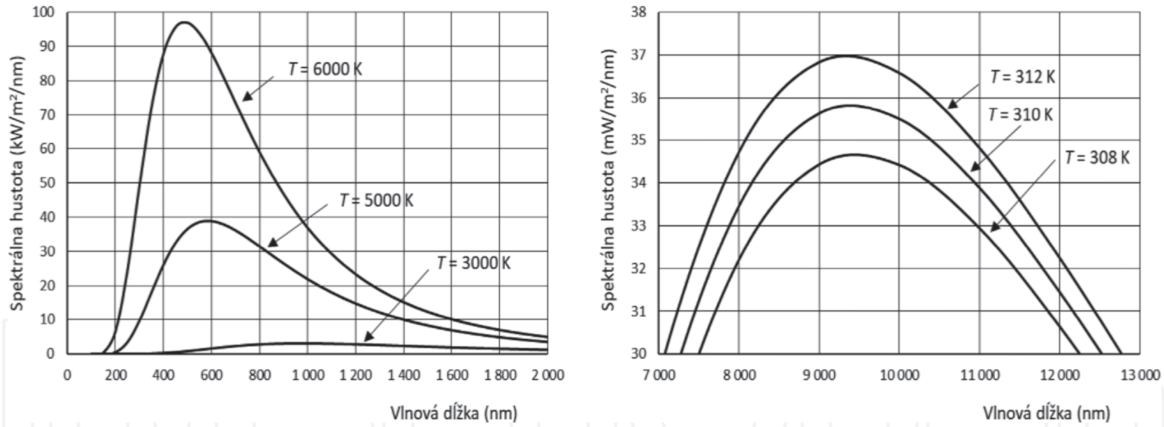

Figure 8.
Spectral density of thermal radiation intensity vs. a wavelength.

High-temperature heat sources are used as heat sources in thermotherapy or as sources for lighting. As can be seen from the graph, the total energy that falls into the optical band (350–700 nm) is only a small part of the total energy expenditure of the source. The light efficiency of these sources is very low, and therefore they are replaced by sources with significantly higher efficiency (discharge lamps, LEDs) for lighting purposes.

From a physiological point of view, the spectrum of heated sources is the most like to the natural light of the Sun. Besides, incandescent sources have high thermal inertia and therefore do not flash when supplied with 50 Hz AC power. The main disadvantage of lighting is low light efficiency. They are preferred as heat sources because most of the radiation spectrum is in the infrared range.

Note: The source temperature results from the analysis of the radiation spectrum. Optical pyrometers use this option to measure very high temperatures. By determining the maximum spectral density in the spectrum of space radiation, the temperature of the Universe was determined to be approximately 3 K. It is one of the pillars of the theory of the origin of the Universe—the Big Bang.

The classical heated sources are incandescent bulbs. The basic modification is a vacuum bulb with a tungsten filament. They have a low light efficiency and a short lifetime due to the evaporation of the tungsten filament, and thus it's thinning. The bulbs filled with inert gas (halogen) improve their efficiency and durability.

Another improvement of light sources represents halogen (krypton, xenon) high-pressure arc lamps, which have a favorable emission spectrum (practically white light), high luminosity, and light efficiency. They use the principle of primary electric arc radiation and subsequent modification of the radiation spectrum using a halogen filling. They are used as sources of intense white light in projectors, sources of white light in optical spectroscopy, and bodies for lighting small or large spaces, e.g., the lighting of the operating area in surgery, dentistry, etc.

1.6.3.2 Thermovision and thermography

Thermovision is a diagnostic imaging method that uses infrared (thermal) radiation from the bodies with non-zero thermodynamic temperature. The average body surface temperature is approximately 310 K (37°C). This corresponds to the spectrum of electromagnetic radiation with a maximum spectral power density at the wavelength of $\lambda_m \approx 9.3$ μm, according to Planck's law. Semiconductor sensors detect the thermal radiation, e.g., InSb is most sensitive to the radiation with a wavelength around $\lambda \sim 5$ μm. At this wavelength, the temperature change of $\Delta T = 1$°C causes the relative power change of 3%. The detector enables detecting the relative change of the power of incident radiation up to 10^{-4}. It allows evaluating the temperature change better than 0.1°C.

A thermographic camera allows the thermal imaging of observed objects. It works on the same principle as a conventional digital camera, but instead of visible light, it is sensitive to infrared radiation. The optical system is transparent only for infrared radiation but is opaque for visible light. CMOS chips are used for the detection of radiation. They are less noisy in the IR region than CCD chips that mainly use conventional cameras. The amplitude of the signal of the individual sensor pixels is color-coded so that a color map of the photographed object displays the monitor of the camera or a connected computer.

In biomedicine, thermovision or thermography is a diagnostic tool allowing to discover diseases that lead to a change of body surface temperature. E.g., inflammatory processes, or not very deep tumors lead to an increase in temperature, reduced blood flow to the limbs due to thrombosis or stenosis results in a decrease in temperature. An example of a thermographic image is in **Figure 9**.

The picture displays a thermographic record of a breast examination, which shows cancer in the right breast (red color indicates an increased temperature). In medical diagnostics, thermography is the most often used for the orientational diagnosis of breast tumors, monitoring the subcutaneous inflammation, or monitoring of the postoperative state. The so-called differential diagnostics, when paired organs, e.g., arms, legs, breasts, are photographed and compared to each other. The different images indicate the changed function of one of them.

1.6.3.3 Low pressure lamps

Another source of incoherent optical radiation is a low-pressure gas discharge lamp. A quantum source is characterized by a discrete frequency spectrum of radiation. The lamp bulb is filled with a low-pressure gas so that the individual atoms are independent and have a line spectrum of electron energy levels. After

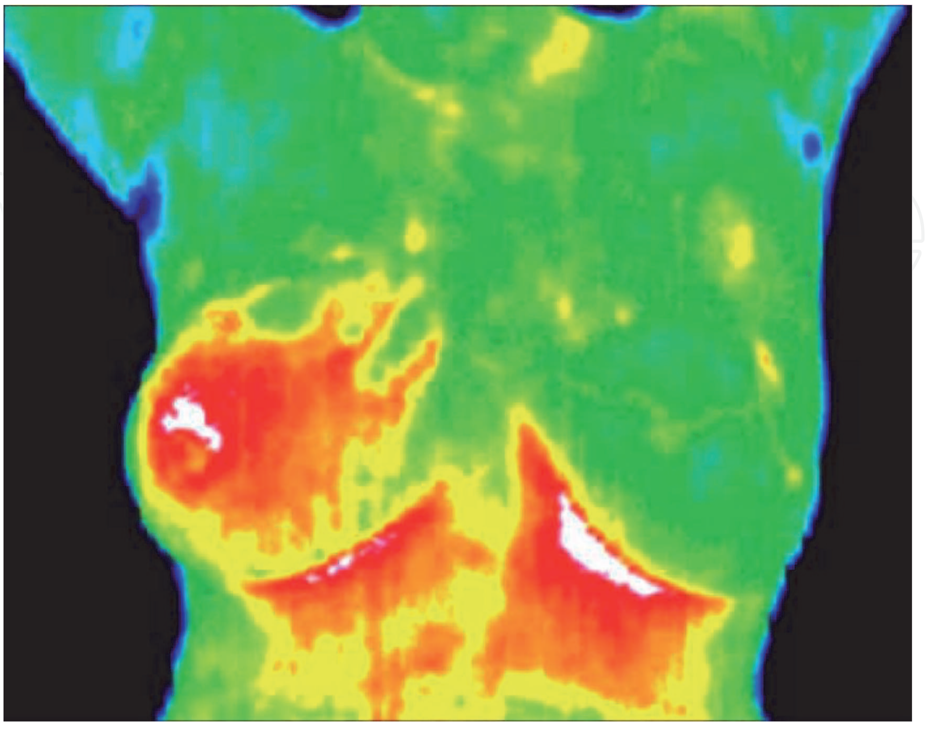

Figure 9.
Example of thermographic record. Source: https://www.researchgate.net/figure/Image-of-digital-infrared-thermal-imaging-Inflammatory-carcinoma-of-right-breast_fig1_260486952.

excitation to a higher energy state, the atom relaxes back to a lower state and emits a photon. The energy of the emitted photon is equal to the difference between the energy of the excitation and the relaxation states. The wavelength of the emitted radiation corresponds to this photon energy, see (68).

The emission spectra of some gases are in **Figure 10**. The upper strip represents a continuous spectrum of a glowing source with a temperature of 6000 K (the Sun). By composing all components of the spectrum, we get white light.

The light intensity of the emission lines, and thus the color of the lamplight, can change as the voltage between the electrodes of the lamp changes. Typical discharge colors are hydrogen—pink to magenta, neon—red to orange, argon—violet to blue, krypton—green to blue-white, xenon—blue to white. Different discharge colors are used for advertising purposes, such as discharge indicators, etc.

Due to the low pressure, and thus the density of the gas, the light intensity of the lamps does not reach too high values. They are, therefore, not suitable for lighting.

Low-pressure discharge lamps also include metal vapor discharge lamps—sodium and mercury. When cold, metals are in a solid or liquid state on the walls of the bulb. The lamps contain a small amount of inert gas (Ne, Ar) so that discharge can arise when switched on the cold lamp. This discharge gradually raises the temperature of the lamp, the metal evaporates and becomes a discharge gas. The light of metallic discharge lamps has a high intensity. These lamps are proper for lighting purposes, e.g., streetlamps. The sodium lamp emits monochromatic light with a wavelength of 589 nm (yellow-orange color). One can encounter sodium lamps in street lighting (yellow lamps).

The mercury vapor discharge contains, in addition to the intense spectral lines: green (546 nm), blue (405 and 436 nm), very intense spectral lines of invisible UV radiation (312 and 365 nm). Mercury lamps, therefore, serve as sources of UV radiation (disinfection of rooms with UV radiation, “mountain sun” in solariums,

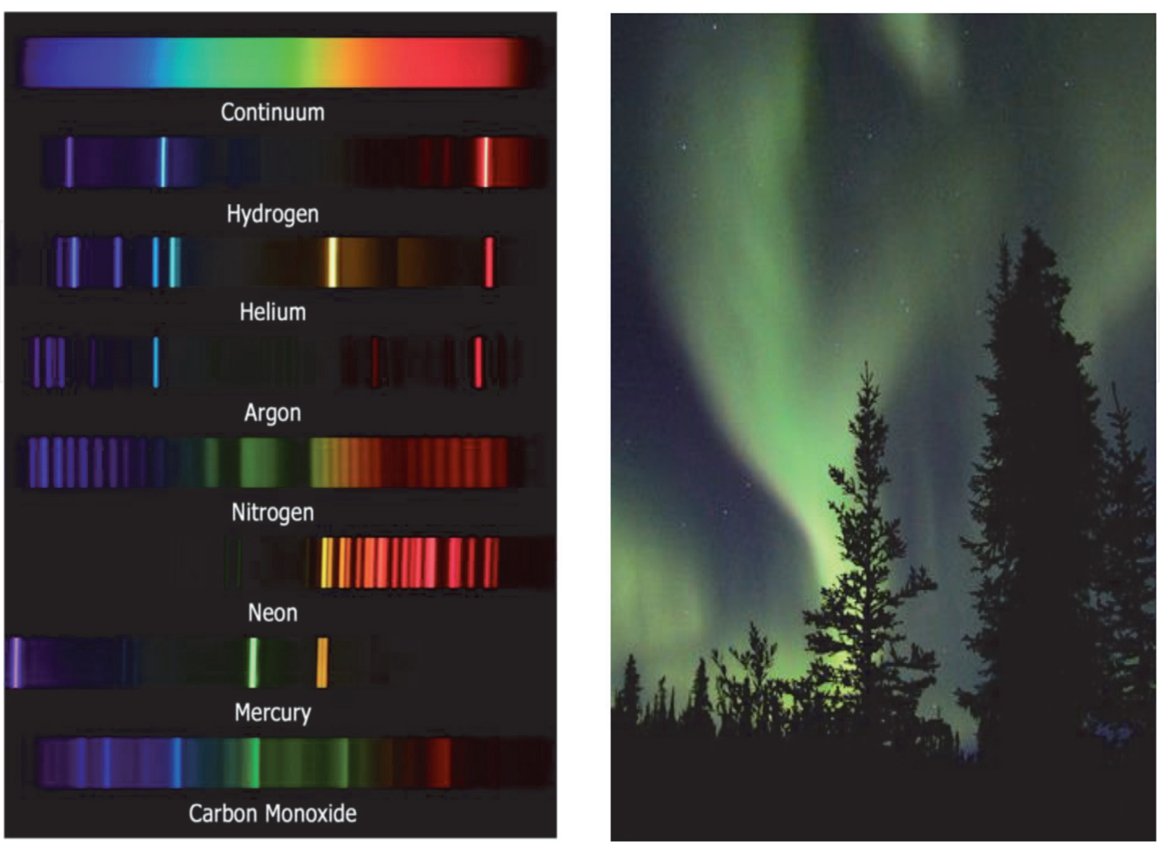

Figure 10.
Emission spectra of some gases and aurora borealis.

for therapeutic purposes in dermatology, etc.). Due to the spectral composition with a predominantly blue color, it is not suitable for lighting purposes.

UV photons excite various substances, which then emit lower energy photons when relaxed. This phenomenon is called *photoluminescence.* This phenomenon is characteristic of substances called *luminophores.* The light emitted from the luminophore has a discrete spectrum typical for the substance. There are known, e.g., banknote security features readable only after UV light illumination.

The mercury lamps are an important example of the use of phosphors. The mercury lamp itself is in a larger bulb, which has a layer of phosphor on the inner surface (most often yttrium-vanadate), which emits red light after irradiation with UV radiation. After combining with the blue and green components of the primary source, it produces white light suitable for illumination. While the mercury lamp bank is of pure silica glass, which transmits UV radiation, the outer bank of the lighting lamp consists of ordinary glass, which does not transmit UV radiation. In this way, the lamp emits only white light without any UV component. It is, therefore, not dangerous for humans.

The lamps of this type can be found in street lighting (white to purple lamps) and lighting in buildings (ordinary fluorescent tubes).

Note: An example of an incoherent quantum source is Aurora Borealis, **Figure 10***. Air molecules (mostly nitrogen) are excited by high-energy particles of the solar wind, which are concentrated in the pole regions by the Earth's magnetic field. The nitrogen then emits blue-green light typical for Aurora Borealis.*

1.6.3.4 Luminescence

In the previous paragraph, we suggested that atoms of substances can be excited to a higher energy state, with the electrons subsequently relaxed back to lower energy levels, either directly or through several intermediate states. The differences in the energy of the states between which the electrons relax determine the emission lines of radiation. If the relaxation follows immediately after excitation (for a time $< 10^{-8}$ s), we speak about *fluorescence,* if the atoms remain in the excited state longer and the relaxation is delayed (for a time $> 10^{-8}$ s), we speak of *phosphorescence.*

The excitation of atoms can take place in various physical ways, which always have in common the supply of the necessary excitation energy of an atom.

The most common phenomenon is *electroluminescence*. A strong electric field accelerates charged particles (electrons) of the gas. They transfer the received kinetic energy due to impacts to the neutral atoms or molecules of gases—we talk about the so-called *impact excitation*. This phenomenon uses conventional electrically powered lamps. The more exotic cases include the Aurora Borealis or lightning during atmospheric discharges.

Another case is *photoluminescence*, where excitation arises due to EM radiation with sufficiently high energy photons (UV, X-rays, or gamma radiation). Photoluminescence (the most often photo-fluorescence) is used both for the analysis of substances and for the detection of radiation. Notable photoluminescence appears at some, especially organic substances, called *fluorophores*. After irradiation with UV radiation, they emit light typical for a given fluorophore. If used in microscopy (excitation microscopy), various macromolecules, tissue, and cell structures can be visible. The principle of photoluminescence utilizes detectors of ionizing radiation (X-rays or gamma radiation), e.g., in sciascopy, CT, or gamma cameras.

Chemiluminescence uses the excitation of electrons due to an exothermic chemical reaction. Phosphorus luminescence is typical due to the slow oxidation of its surface. A special case is *bioluminescence*, where fluorescence occurs because of biochemical reactions. A typical case is the firefly beetle, whose buttock glows due to the oxidation of luciferin. Another example is the luminescence of rotting wood ("luminous wood") or necrotic tissue, where putrefactive bacteria emit light in the process of fermentation oxidation.

An interesting case represents *thermoluminescence*. The mechanism of this phenomenon is slightly different. Some substances, excited by ionizing radiation, enter a quasi-stable excitation state with higher energy. They can remain in this state for a long time (months, years, hundreds of years, etc.). They serve as memory elements that record and integrate irradiation in the form of energy of the excitation state. From this state, the substance can return by heating to a high temperature, which releases the accumulated energy. In this way, from the mineral fluorite, geologists determine the degree of irradiation of the rock during geological development, e.g., by nuclear events.

In biomedicine, such substances are used in personal dosimeters (dose meters—radiation cans) of health care workers who work in workplaces using ionizing radiation (radiodiagnostics, radiotherapy, nuclear medicine, etc.). The dosimeter, that the worker carries with him, is excited by radiation, and the dose information is stored. With the detection device, the dosimeter is "read" at prescribed intervals (e.g., once a month) using thermoluminescence. In biomedicine, such substances are used in the personal dosimeters of healthcare workers employed in workplaces with ionizing radiation (radiodiagnostics, radiotherapy, nuclear medicine). The dosimeter carried by the worker is excited by radiation, and the dose information is stored. The dosimeter is "read" at prescribed intervals (e.g., once a month) with a detection device using thermoluminescence.

The next form of luminescence is *radioluminescence*—luminescence due to excitation by a nuclear reaction (e.g., alpha or beta radiation). E.g., tritium enriched ZnS (the radioactive hydrogen isotope ^3H) excites the ZnS phosphor due to the beta conversion of tritium. It is used, e.g., on the hands of watches or devices working in the dark.

1.6.3.5 Semiconductor light-emitting diodes (LEDs)

Semiconductor sources LED (light emitting diode) use radiant recombination of electron-hole pairs in the PN junction.

In **Figure 11** is the energy spectrum of electrons in a P-type semiconductor with free charge carriers—holes, and N-type with free charge carriers—electrons. If the semiconductors come into contact (figure left), the chemical potential represented by the Fermi level E_F is equalized in the whole P-N system by the diffusion of electrons and holes. An insulating (non-conductive) barrier without free charge carriers is formed in the close contact space. Electrons from semiconductor N cannot get into semiconductor P and recombine with holes. But if we connect the voltage $U = E_g/e$ in the forward direction, where E_g is the width of the forbidden gap in the energy spectrum, the Fermi levels are shifted relative to each other, so that the edges of the conducting and valence bands are aligned. In this case, both electrons and the holes can freely enter the barrier and recombine there. The recombination causes the release of the energy equal to the difference $\Delta E \geq E_g$. In most cases, it transfers to the lattice (thermal transitions). In some cases, the energy is releases in the form of photons (radiant transitions), and the junction thus emits EM radiation in the frequency range around $\lambda \sim h\, c/E_g$. For $U > E_g/e$ is $\Delta E > E_g$ and the wavelength of the photons is shorter. The emitted light has a characteristic color, but it is not monochromatic. Various combinations of elements from groups II–VI (ZnS, CdS, ZnO), III–V (GaAs, GaN, GaAsP, InSb, AlGaAs), or IV–IV (SiC) are used for the PN junction production.

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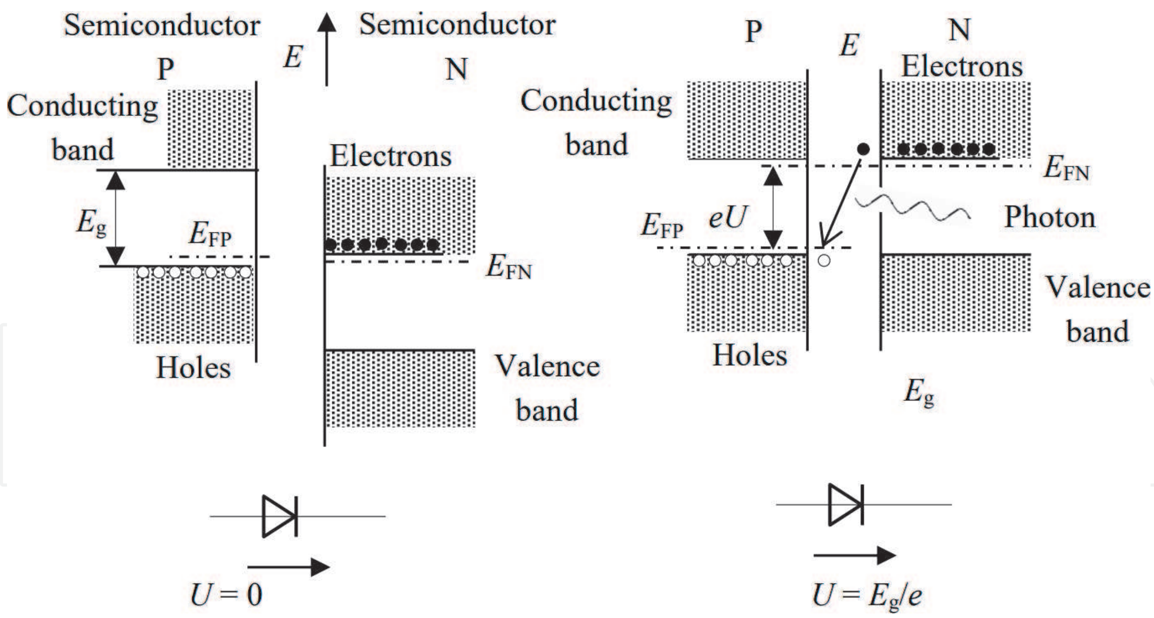

Figure 11.
Radiating PN junction—LED.

Depending on the different width E_g of the bandgap, the junction (LED) emits radiation of different colors. As we see in the **Table 4**, the LED sources cover the entire spectrum from infrared over visible to ultraviolet radiation. By combining LEDs with different colors, other colors can be reached, such as pink, purple, and especially white.

Turn in the use of white LED sources for lighting purposes (energy-saving LED bulbs) was the invention of a highly efficient blue LED based on GaN (Nobel Prize in Physics 2014) with maximum radiation at a wavelength of 465 nm. The white color is achieved by the luminophore YAG (yttrium aluminum garnet), which, after irradiation with the blue light of a GaN diode, emits broad-spectrum light in the band of 500–700 nm. The composition of the blue diode light and the phosphor light produces white light. These LEDs are used in energy-saving lighting fixtures.

Composing R-G-B (Red Green Blue) colors of different light intensities, we can create any visual color. Using LEDs with these colors, we can "mix" light with any

Light color	Wavelength λ/nm	Voltage U/V	Material
Infrared	>760	<1.63	GaAs, AlGaAs
Red	610–760	1.63–2.03	AlGaAs, GaAsP, AlGaInP, GaP
Orange	590–610	2.03–2.10	GaAsP, AlGaInP, GaP
Yellow	570–590	2.10–2.18	GaAsP, AlGaInP, GaP
Green	500–570	2.10–4.00	GaP, AlGaInP, AlGaP—traditional InGaN/GaN—pure green
Blue	450–500	2.48–3.70	ZnSe, InGaN, SiC
Violet	400–450	2.76–4.00	InGaN
UV	<400	3.0–4.1	InGaN (385–400 nm) Diamant (235 nm) BN (215 nm), AlN (210 nm) AlGaInN (up to 210 nm)

Table 4.
Various color LEDs.

other color. This system is used by LED displays (screens of TV and computers, mobile phones, etc.), which consist of a fine network of three RGB-LED radiant elements. By changing the voltage on the individual elements, the color of the image changes.

Commercially accessible RGB LEDs with four terminals are also available. They have one common terminal, and three for each RGB segment placed on one chip. It allows controlling the color of the emitted light by changing the voltage on the three terminals. They come in useful in different signal lights. As there is a direct conversion of electric energy into visible light, the LED sources have high light efficiency of 140–150 lm/W. For comparison, a vacuum bulb with tungsten filament has light efficiency of 10–12 lm/W, halogen bulb 20 lm/W, compact fluorescent lamp 50–60 lm/W, halogen lamp 100 lm/W, low-pressure sodium lamp up to 180 lm/W. The luminosity of a 5 W LED is the same as that of a standard 40 W bulb. Another parameter of the light quality is the color temperature equivalent, which corresponds to the temperature of a thermal source with the same spectrum. E.g., 6000 K corresponds to sunlight (so-called cold white with an even representation of all wavelengths). Widely used is 2700 K light, corresponding to halogen bulb (so-called warm white with reduced blue and green component).

Lighting with different spectral compositions has different effects on humans (vision, production of melatonin or vitamin D, etc.) Intensive research of LEDs currently carries out to increase the efficiency of the conversion of electricity into light and to broaden the spectrum of radiation. In addition to visible light, one uses LEDs as sources of infrared and ultraviolet radiation.

The advantage of LEDs is that they allow a point, resp. local application, e.g., local heating of tissue by IR radiation or local irradiation by UV radiation. In the **Table 4**, there are LED sources for all bands of radiation up to a UV wavelength of 210 nm. UV LEDs allow, e.g., making visible the luminescent security features of banknotes, chip cards, etc.

The photosensitivity of microorganisms is related to the absorption spectrum of DNA with a maximum around the wavelength of 260 nm. LEDs with a range of 250–270 nm are proper for disinfection and sterilization.

LEDs can have small dimensions (under 1 mm). It is advantageous in endoscopes for illumination of the examined internal organ or in laparoscopic surgery to illuminate the operating field. The integration of LED with photodetector creates an optical coupler for the galvanic separation of electronic circuits. The connection of LED to optical fiber allows leading light anywhere.

Due to incoherence, the light of the LED is proper for the transmission of energy (lighting, irradiation, heating), but it is not capable of the transmission of information. Where require coherent light, LASER is suitable as the source.

Other promising light sources include organic semiconductor light-emitting diodes—OLEDs. The semiconductor material can be individual macromolecules or polymers. They make it possible to generate low-cost diodes with low operating voltage, high contrast, and a wide range of wavelengths. Another advantage of polymer OLEDs is their easy formability and mechanical flexibility. They are thus suitable for creating displays for mobile devices, such as mobile phones, digital cameras, or televisions.

1.6.4 Sources of coherent optical radiation—LASER

If we need to utilize the wave properties of EM radiation, we use a source of coherent radiation. Because of a single source (antenna), the radiofrequency and the microwave radiations are mostly coherent. The origin of optical radiation is random spontaneous relaxation of many atoms of matter so that the resulting radiation consists of many uncoordinated or minimally coordinated elementary waves with different frequencies and phases. The resulting waving is, therefore, incoherent.

If we want to create a coherent optical wave, all excited atoms must relax together and in phase. It is achieved by *stimulated* relaxation. At first, the whole system of atoms of the substance must be excited to a higher energy quasi-stable state with a long relaxation time. After the excitation, the external resonant stimulus must induce (stimulate), at one moment, the simultaneous relaxation of all atoms. All emitted photons have properties of the stimulating one, it is, the same frequency, phase, and propagation direction. Because of many initial stimuli, elementary waves with various frequencies and directions arise. The demanded frequency and direction are selected by an optical resonator, which amplifies the resonant waves and suppresses the non-resonant ones with other frequencies and different directions. Thus, the energy of the pumped system concentrates on producing one coherent wave with a given frequency, phase, and propagation direction. This system calls LASER (Light Amplification by Stimulated Emission of Radiation).

The system takes energy continuously, and the generated waves are also taken continuously from the resonator, e.g., through a semi-transparent mirror at one of the ends of the resonator. In this case, a *continuous wave* (*continuous laser*) arises. It is about generating a narrow beam of coherent radiation with relatively low power from a few mW to hundreds of W. The continuous lasers with infrared light are used, e.g., in *laser scalpels* for soft tissue surgery. The possibility of effectively focusing a coherent beam to a diameter approximately equal to the wavelength, and the thermal effect, which causes the blood coagulation and closing the fine capillaries, is advantageous. It allows very precise, fine, and bloodless cuts. The laser can be attached to a computer-controlled manipulator and thus perform a computer-controlled operation. *Operational robots* use this option. Blue light lasers with better focusing are used for eye surgery. Blue light cannot coagulate, but this is not necessary for eye surgery, especially the cornea and lens.

The second option uses the pumping energy of a system of atoms during a longer time interval and the sudden emission of all energy E in a short pulse of coherent radiation—*pulsed laser.* If the pulse length τ is small, the power $P = E/\tau$ of the radiated pulse is very large. Thus, extreme values of radiation power are achieved, (e.g., for $E = 1$ J and $\tau = 1$ ps is $P = 1$ TW), e.g., to investigate nonlinear phenomena. In medicine, pulsed laser is use in laparoscopic *laser lithotripsy.* A series of short power pulses heat the kidney or gall stones in small points, which are mechanically disturbed due to the temperature gradient and the associated gradient of mechanical stress. After applying several series of impulses, the stone breaks down into small parts easily washed away.

Substances with a discrete spectrum of energy levels make possible a laser effect. The simplest case is a three-level system, **Figure 12***. The electrons are excited from the ground level E_1 to level E_2. The electrons immediately relax to lower levels of E_1 and E_3. The level of E_3 must be metastable, which means, electrons remain on it for a long time and accumulate there. The electrons will gradually fill the E_3 level. The excitation takes place either by irradiation with an external light source, most often a Hg gas lamp (gas and crystal lasers), or by an electric voltage (semiconductor laser). If a resonant photon with energy $E_s = E_3 - E_1$ occurs in the system, a stimulated transition of all electrons from the state E_3 to the ground state occurs. The accumulated energy radiates in the form of photons with energy $E_L = E_s = E_3 - E_1$—stimulated emission of photons with the same properties as the first initiation photon (frequency, phase, propagation direction). The laser includes a resonator with a length of $N\,\lambda\,L$ (N is an integer), which is excited by resonant photons having a defined wavelength and longitudinal propagation direction. The resonator is an enclosed space bounded by two parallel mirrors M (total) and SM (semi-transparent or*

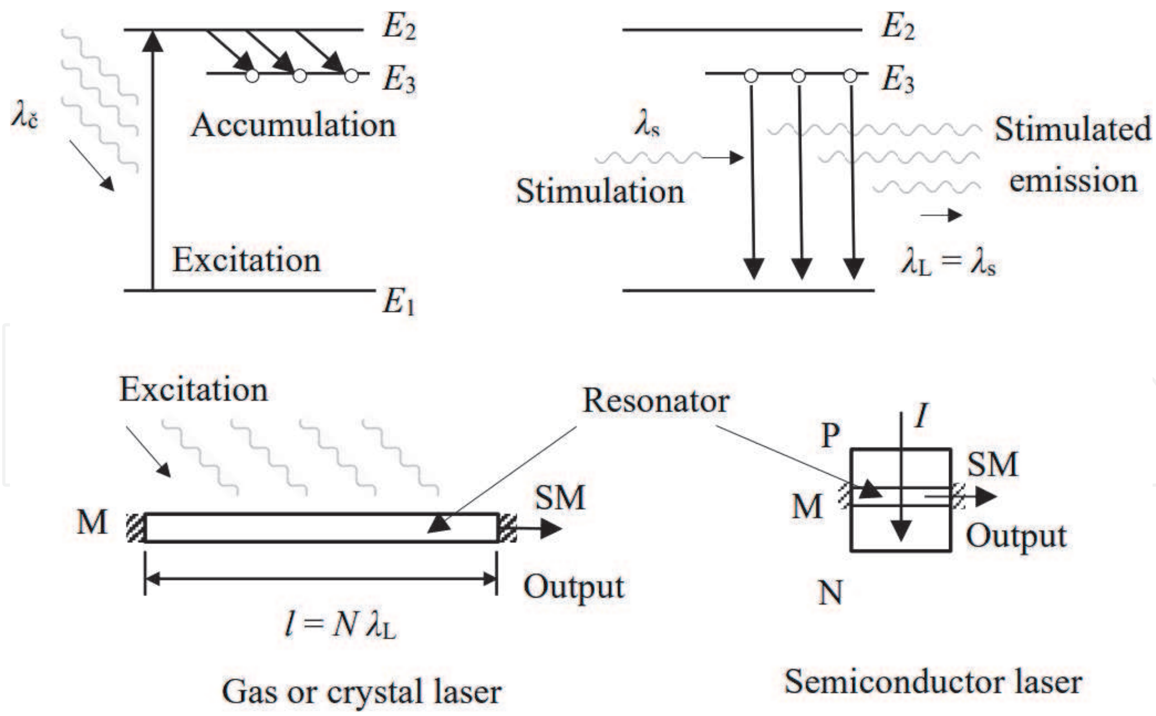

Figure 12.
Laser principle.

electronically openable in the case of a pulsed laser). Photons that do not have the exact resonant frequency and longitudinal direction will not excite the resonator.

The resonant wave reflects many times in the resonator and induces further coherent stimulated transitions to amplify the resulting wave. In a gas laser, the resonator has the shape of a tube with active gas. In a crystal laser, the resonator is the active crystal of a cylinder shape, in a semiconductor laser, the resonator represents a thin layer of the PN barrier. The coherence length of the emitted wave is many times larger than the length of the resonator. Gas lasers reach a wave coherence length of tens of centimeters to hundreds of meters, semiconductor lasers of up to 20 cm, and special fiber lasers of up to 100 km.

Note: Semiconductor lasers use a similar principle as LEDs, but used semiconductors are enriched with impurities, creating a metastable level in the forbidden band of their energy spectrum. In advance, they have a resonator, which makes the technology of laser diode production more demanding than the production of LED. Today, semiconductor laser diodes are very popular, and we can meet them, e.g., in laser pointers.

The wavelength of the laser radiation determines the active substance, i.e., the difference of energies $E_3 - E_1$ and tuning of the resonator. Some active substances have more relaxation levels, and therefore the laser effect can occur at several wavelengths. The demanded one selects the resonator by tuning from these wavelengths.

The laser light is monochromatic, and therefore a resonant absorption in different substances gets some possibilities of its application.

There is an example of the spectra of hemoglobin and water in **Figure 13**. The maximum absorption of IR radiation in water is at $\lambda \approx 3.0$ μm, which corresponds to radiation (λ = 2.94 μm) of the erbium-doped yttrium-aluminum-garnet (Er:YAG) laser. This gets possible, the surface of hard tissue correcting, e.g., in dentistry, by replacement of a drill with a painless laser. Similarly, a holmium-doped YAG (Ho:YAG) laser (λ = 2.1 μm), use in laser lithotripsy of urinary stones, where IR light is applied, using a catheter with an optical fiber through the ureter, directly into the stone.

On the contrary, the radiation of an Nd:YAG laser (λ = 1.064 μm) has a small attenuation in water and in soft tissue and thus a greater penetration depth. It is proper for the treatment of tissue in greater depth. It is a part of a laser scalpel. Radiation of the Nd:YAG with KTP laser, **Table** 5, with a wavelength λ = 532 nm,

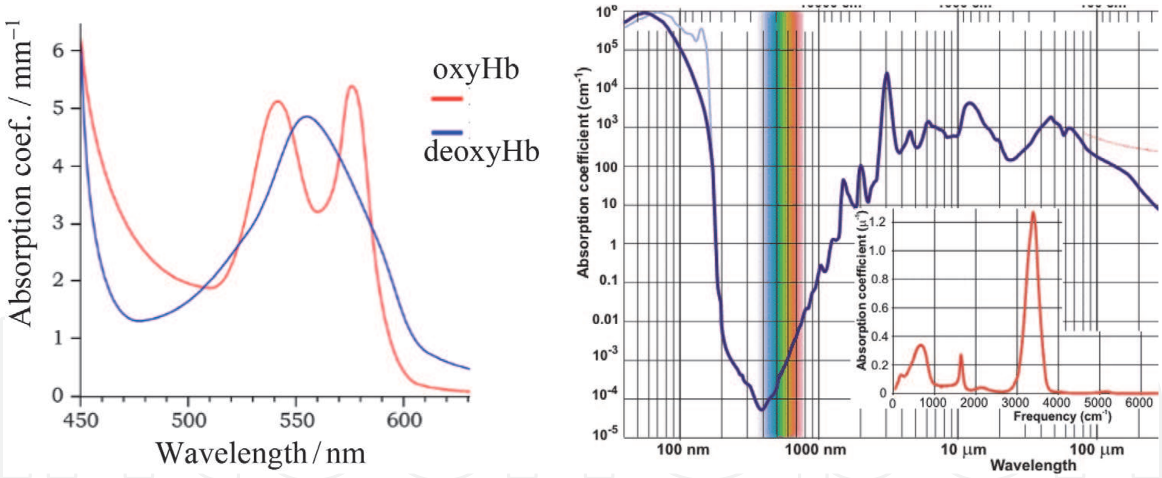

Figure 13.
Absorption spectra of hemoglobin (left) and water (right).

Material	Wavelength λ/nm	Color of the beam	Application
		Solid-state lasers	
Al_2O_3:Cr (ruby)	694.3	Red	Dermatology
Nd:YAG Nd:YVO	1064	Infrared	Surgery, laser scalpel
Nd:YVO_4 + KTP	532	Green	Treatment of angioma
Ho:YAG	2100	Infrared	Surgery, lithotripsy, stomatology
Er:YAG	2940	Infrared	Stomatology, absorbed in water
		Gas lasers	
He-Ne	633 and 543	Red, green	Holography navigation
Ar	488 and 514	Blue, green	Ophthalmology, absorbed by hemoglobin
CO_2	10,600	Infrared	Dermatology, onychomycosis, cutting laser scalpel
Excimer ArF, KrCl, KrF, XeCl, XeF	193–351	Ultraviolet	Ophthalmology, laser ablation, cornea correction
		Liquid dye lasers	
Rhodamine	570–650	Yellow to red	Dermatology, absorption by oxyhemoglobin
Coumarin	460–540	Green	Ophthalmology, surgery
		Semiconductor diode lasers	
GaAs	560 and 808	Red, infrared	Photoplethysmography
GaAlAs	670–830	Red, infrared	Telecommunication, CD players
AlGaInP	650	Red	DVD players
Ga(In)P, Ga(In)N	405 and 550	Blue, red	Blu-Ray players

YAG—Yttrium Aluminum Garnet ($Y_3Al_5O_{12}$); YVO—Yttrium Orthovanadate (YVO_4); KTP—Kalium Titanyl Phosphate ($KTiOPO_4$), nonlinear optical material used for doubling the wave frequency (half-wavelength 1064 → 532 nm).

Table 5.
Different types of lasers.

corresponds to the absorption maximum of oxyhemoglobin. It is, therefore, strongly absorbed in the blood, and is used, e.g., for the treatment of angioma (highly bloodied superficial benign tumor) by selective overheating.

Precise ophthalmology operations utilize short-wavelength lasers (green, blue, UV). An excimer laser (unstable molecules of inert gas and halogen) is used, e.g., for corneal correction, and thus correction of myopia, hyperopia, or astigmatism. Lasers with different wavelengths are widely used in dermatology. Because of the possibility to focus the collinear beam of coherent waves on the spot of the dimension of a wavelength and precisely locate the action of the laser, it is widely used in ophthalmology, neurology, or surgery. Semiconductor diode lasers represent a significant advance in laser technology. IR and red most often consist of a doped GaAs semiconductor, blue to ultraviolet on GaN, or GaP. The rate and type of doping elements can vary the wavelength over a wide range.

Since the size of the radiating surface is very small (several μm), it generates a diverging beam. It changes to a parallel beam by a small lens. Due to the small length of the resonator, the coherence length is not greater than 20 cm. The spectral width of the LED emission lines is greater than 1 nm, but it is sufficient for most applications.

The advantage of semiconductor diode lasers is their small size, which makes them suitable for portable devices like laser pointers, CDs, DVDs, and Blu-ray players, laser printers, etc. It is possible to connect the laser diode directly to an optical fiber and transmit light to any place and over a long distance. Another advantage is in the electric excitation, which allows easy modulation of the light beam by an electrical signal. They are, therefore, useful in optical communications, from simple optical couplers to long-distance transmission systems. Laser diodes are manufactured for a wide range of power from units of mW to tens of W, which provide many applications in medicine.

1.6.5 Sources of ionizing EM radiation

Ionizing by radiation causes the ionization of atoms or molecules or a change in chemical bindings. Shortwave EM radiation or radioactive particle radiation (alpha, beta, protons, neutrons) exhibits the ionizing effect. The carriers of the EM radiation energy are photons with energy $E = h\,c/\lambda$. Ionizing effects occur at energies of photons above 10 eV, chemical effects already at energies of several eV (e.g., dissociation energy of water is about 5 eV), which corresponds to EM radiation with wavelengths of approximately $\lambda < 250$ nm. This corresponds to UV-C ultraviolet radiation (100–280 nm), X-rays, and gamma radiation.

UV sources were described in the previous paragraph. E.g., an excimer laser generates the ionizing UV-C radiation.

The next section gets an overview of the sources of X-rays and gamma rays, used in medical diagnostics and therapy.

1.6.5.1 X-rays sources

X-rays represent the EM radiation with wavelengths from 10 nm up to 10 pm, i.e., with photon energy from 100 eV to 100 keV. X-rays, like optical radiation, are generated by the relaxation of electrons in atoms from higher energy levels to lower ones after the previous excitation, most often by electrons, accelerated in an electric field (accelerator). Due to the high energy of X-photons, only the atoms with a high atomic number that have sufficiently low energies of deep bonded electron states, and simultaneously hard fusible metals, can be used to generate this radiation. Tungsten is the most often used. In an accelerator with a voltage U, the electron obtains the kinetic energy $E_k = e\,U$. After impact with the tungsten target anode, the electron transfers its energy to the atoms in the surface layer. Most of the energy of the incident electrons converts into internal thermal energy so that the target heats up strongly, and into emission of the electrons from the surface layer. Some of the incident electrons cause excitation of the bound electrons to higher states. At a sufficiently high voltage U, the bound electrons are excited from deep states up to the conduction band, see **Figure 14**. Electrons from higher energy levels of the conduction band or near bound states then relax into the emptied deep states.

The maximum energy of photons is equal to the kinetic energy of incident electrons.

$$\frac{1}{2}\,m\,v^2 = e\,U = \frac{h\,c}{\lambda_{\min}}, \quad \text{from where } \lambda_{\min} = \frac{h\,c}{e\,U}, \tag{70}$$

where U is the accelerating voltage. E.g., for U = 40 kV is $\lambda_{\min} = 31 \times 10^{-12}$ m.

The minimum wavelength can thus be varied through the accelerating voltage U.

Transitions from a wide conduction band E_c generate photons with a continuous energy spectrum, the so-called *braking radiation*, with the lower limit of the wavelength $\lambda_{\min}$, **Figure 14**. Transitions from near bound levels to empty deep levels emit the so-called *characteristic radiation* with precisely defined wavelengths, which produce sharp peaks in the spectrum.

In **Figure 15(a)**, there is a classical X-rays source—a vacuum X-rays lamp. Heating filament supplied by voltage U_h heats the cathode K, which emits electrons due to thermionic emission. They move in an electric field with a voltage accelerating U to the anode A. The anode is a rotating copper disk with a layer of tungsten on an inclined surface. Disk rotation reduces overheating at the point of electron beam impact. X-rays are emitted from the point of impact of the electrons.

With the development of nanotechnology, a cathode with cold electron emission of electrons has been developed. These CNTs (Carbon Nano Tubes) cathode has very fine carbon nanotubes on the surface. After approaching a grating electrode with a positive potential (from ten to one hundred volts), a strong electric field is created on the sharp tips of the nanotubes. It causes an electron discharge (electron emission). The electrons then penetrate through holes in the grating electrode and form an electron beam. The cathode has a dimension of tenths of an mm and is relatively cold. It allows realizing miniature devices. One important invention is the

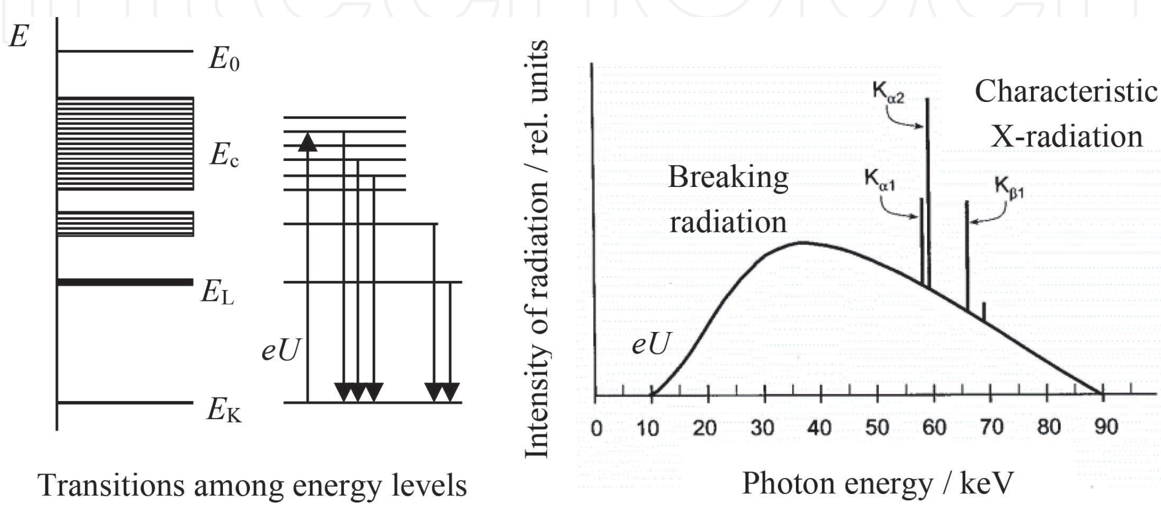

Figure 14.
Principle of rising and spectrum of X-rays.

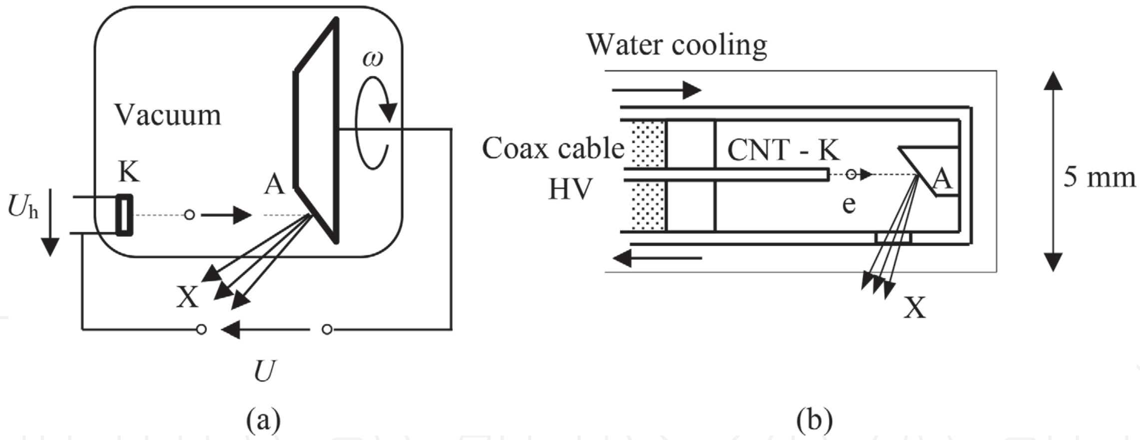

Figure 15.
X-ray sources (a) vacuum X-rays lamp, (b) micro X-ray s tube.

Micro X-rays Tube, **Figure 15(b)**. Electrons emitted from the CNT cathode electrostatically focus on the tungsten target. The voltage between cathode K and anode A supplied by the coaxial line is up to 50 kV. Accelerated electrons thus, after hitting the anode, generate X-rays, which emerge from the tube through a window. The tungsten anode warms by incident electrons, and therefore the generator is housed in an outer tube that supplies water to cool the anode. The power of emitted radiation is limited to ensure sufficient cooling. Another advantage of the CNT cathode is the possibility to control its current by the voltage at the grid with a very short time constant. It allows pulse modulation of the generated X-rays and thus to achieve a high instant radiation intensity at low average power. At a maximum cathode current of 300 μA, the microgenerator offers a dose rate of up to 0.6 Gy/min, which is sufficient for many applications. The entire X-rays probe is about 5 mm in diameter and a few centimeters long. In medicine, microgenerators are used mainly in brachytherapy (*Greek: brachys—close*) by placing the emitter directly in the place to be irradiated, e.g., tumor. The dimensions of the microgenerator allow us to place it in a catheter and insert it through a vessel, urinary, or digestive tract into the appropriate site and then turn the switch on and off for the required time.

1.6.5.2 Sources of gamma radiation

Gamma radiation is EM radiation with a photon energy of 1 MeV to 10 GeV, or with wavelengths of 10^{-12} to 10^{-15} m, which is emitted from the nuclei of atoms (nuclear radiation). Similarly, to optical radiation or X-rays, which is produced by the transition of electrons from higher energy levels to lower ones, gamma radiation is caused by the relaxation of excited nuclei. While the energies of the electron states have values from units of eV to 100 keV, and the energy of the emitted photons corresponds to this, the energy of the nucleus states has values from 100 keV up to tens of GeV. The excitation of nuclei occurs due to nuclear transformations or the impact of gamma radiation, neutron, proton, or alpha radiation on atomic nuclei. Natural sources are radioactive substances that occur in nature, such as uranium, radium, radon, etc. A significant amount of radioactive material is found in the Earth's crust, and the heat released during its transformations is one of the Earth's heat sources, together with the Sun, which maintains a friendly ambient temperature. Radioactive preparations as sources of gamma radiation are mostly artificially produced. In medicine, gamma radiation uses diagnostics because of its low attenuation in the human body. Molecules of chemicals participating in metabolic processes in the body are "labeled" with atoms of a radioactive substance (some atoms in the molecule are replaced by similar radioactive atoms that do not change their chemical properties). These molecules are called radio markers and radiopharmaceuticals. After application to the body, the radiopharmaceutical concentrates at the site where it uses the body. These sites thus appear in the increased production of gamma radiation. The gamma camera displays these places, and based on the created images, it is possible to analyze physiological processes in the body, and thus disease processes in the body. Modern nuclear imaging methods include SPECT (Single Photon Emission Tomography) and PET (Positron Emission Tomography). The discipline of nuclear medicine deals with this issue in detail.

The most often used sources of gamma radiation for SPECT are technetium ^{99m}Tc, krypton ^{81m}Kr, iodine ^{131}I. Each radioactive preparation has different energy of emitted photons, and therefore a different function in the body. The PET method uses the annihilation of positrons with electrons accompanied by the production of a pair of gamma photons. They have the same energy and propagate in opposite directions. Radioactive preparations generate positrons due to the transformation of some neutron-deficient nuclei. The proper biogenic elements are carbon ^{11}C, nitrogen ^{13}N, oxygen ^{15}O, and fluorine ^{18}F. At the conversion of the nucleus, the proton converts to a neutron and a positron. The positron is an antiparticle to an electron, and when a particle and an antiparticle meet, both annihilate and form a pair of photons.

Example 7. Gamma conversion of iodine ^{123}I nucleus.

Nuclear medicine uses unstable isotopes of nuclei of different elements as sources of gamma radiation. Isotopes of elements, which the body uses in its organs for their activities, are used for diagnostic purposes. For thyroid examination, the unstable iodine isotope ^{123}I is proper. During the nuclear transformation, the nucleus captures an electron from the lowest state of the electron shell. The transformation obeys the equation

$$ {}^{123}_{53}\mathrm{I} + -1_0\mathrm{e} \rightarrow 52_{123}\mathrm{Te} + \gamma(0,16\ \ \mathrm{MeV}). \tag{71} $$

The reaction produces tellurium and releases a gamma photon with an energy of 160 keV, which corresponds to the wavelength.

$$ \lambda = \frac{h\,c}{E_{\mathrm{f}}} \approx 7,7 \times 10^{-12}\ \mathrm{m}, $$

corresponding to electromagnetic radiation from the gamma band.

Example 8. Annihilation of an electron-positron pair.

In nuclear medicine, the isotope of the fluorine atom ^{18}F, unstable with a half-life of 110 min, changes according to the equation

$$ {}^{18}_{9}\mathrm{F} \rightarrow 8_{18}\mathrm{O} + {}^{0}_{1}\mathrm{e}^{+}. \tag{72} $$

The second particle is the positron, antiparticle, which has the same mass and opposite charge as the electron. When the positron encounters an electron while moving from the point of origin, both particles disappear—*annihilate,* producing two identical gamma photons. The reaction preserves energy and momentum, and the quantities must be considered relativists. We assume that the momentums of the particles before the collision are small and can be neglected.

$$ \begin{gathered} m c^2 + m c^2 = E_{\mathrm{f}1} + E_{\mathrm{f}2}, \\ 0 = \mathbf{p}_{\mathrm{f}1} + \mathbf{p}_{\mathrm{f}2}. \end{gathered} \tag{73} $$

The second equation shows that the photons have the same momentum and opposite direction, i.e., they have the same energy. From the first equation we get

$$E_{\mathrm{f}} = m c^2 = \frac{h c}{\lambda}. \tag{74}$$

The energy of the photons is E_{f} = 512 keV and the corresponding wavelength λ = 2.4 × 10^{-12} m, which corresponds to gamma radiation.

1.7 Detection of electromagnetic waves

Another part of the transmission system is a detector of the radiation. Like sources, detectors depend on the function for which they are intended and the wavelength of the radiation. There are three groups of detectors—wave detectors, power detectors, and ich detect quantum detectors. In the first group are detectors, which detect the amplitude, frequency, and phase of the wave. Wave detection is possible only in the case of coherent waves. In the second group are detectors, which evaluate the energy or power of the incident radiation. They use a change of temperature of the sensor, due to the absorption of radiation. Quantum detectors use the quantum nature of radiation—photons and the energy spectrum of the detection sensor.

1.7.1 Wave detectors

Wave detectors provide information about the wave quantities—amplitude, frequency, phase, and polarization. One of the detection methods is the use of antennas and the conversion of wave quantities into voltage or current in the detection antenna. Antennas are useful mainly for radio waves and microwave ranges. Another method utilizes wave interference. This method is used mainly in the range of optical waves.

1.7.1.1 Antennas for receiving EM waves

The basic elements of antenna systems are electrical or magnetic dipole sensors. Several basic types of antennas are in **Figure 16**. The first type is a rod antenna, figure (a), in which the EM wave induces electrical voltage U. To achieve the maximum detection efficiency, the resonant mode of the antenna is tuned, i.e., the total antenna length *λ/2—the half-wave dipole*. The elementary dipole is usually a part of more complex antenna systems, where other elements serve to shape the radiation pattern of the antenna, and thus increase its gain and directivity. Figure (b) shows a Yagi antenna, used to receive a TV signal, figure (c) is a parabolic antenna for receiving astronomic signals. A similar but smaller parabolic antenna serves for telecommunication connections and the reception of TV satellite signals. Figure (d) shows a special PIFA antenna (Planar Inverse F-Antenna), used in mobile devices (mobile phones, GPS receivers, etc.).

At frequencies around 1 GHz and above, PIFA is so small that it can fit in small instruments. The example in the picture has the dimension of the width of a mobile phone. Another type is a $\lambda/4$ antenna above the conductive base plane, figure (e), where the second $\lambda/4$ part of the half-wave dipole is formed by mirroring. An example is, e.g., rod antenna (f) of WIFI communicator, or waveguide field detection probe (g). This elementary detection probe is, e.g., a part of the microwave funnel antenna (h)—the funnel adjusts the radiation pattern and impedance

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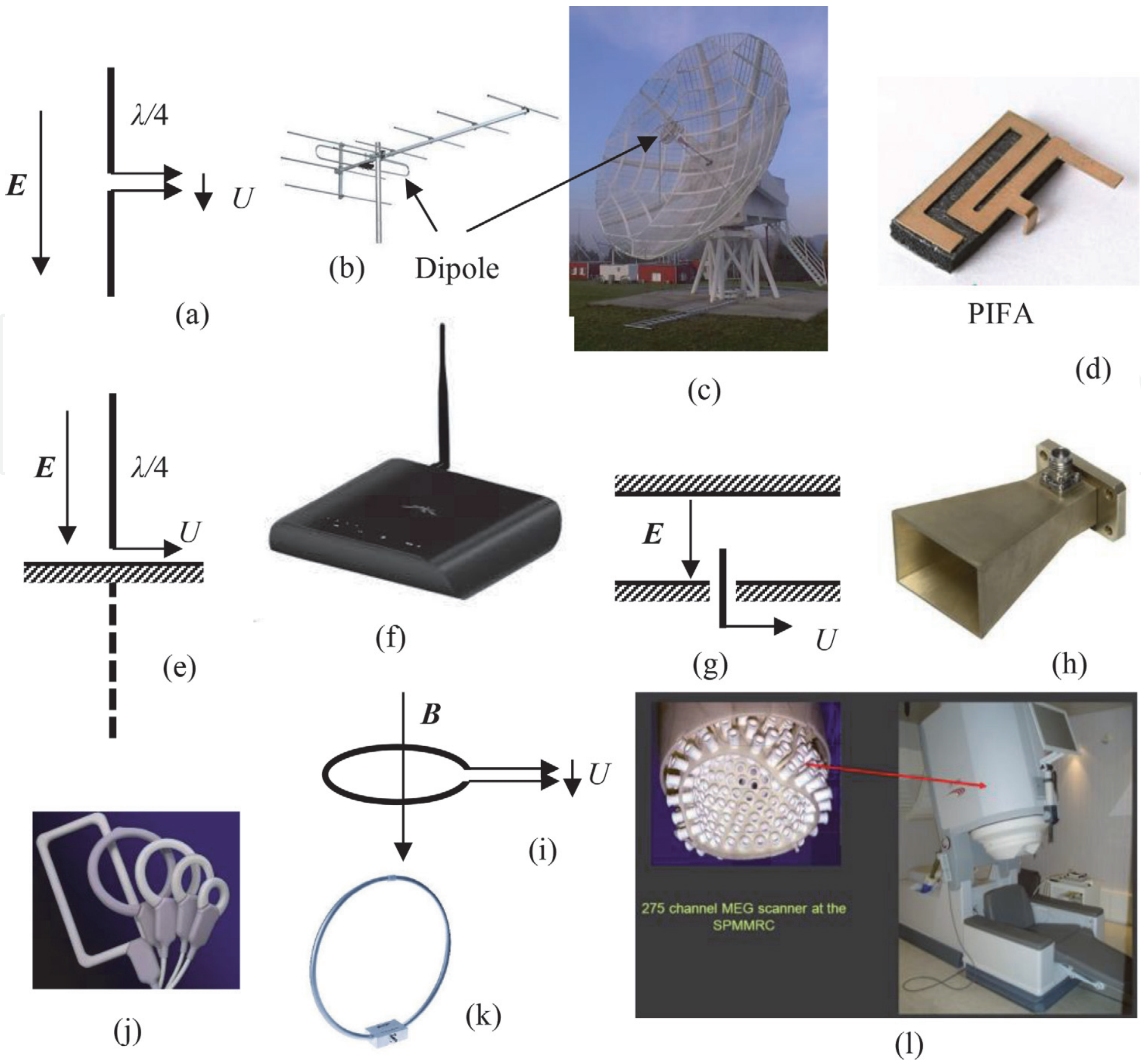

Figure 16.
Different types of antennas. (a) dipol antena, (b) Yagi antena, (c) parabolic antena, (d) PIFA antena, (e) quater wavelength antena, (f) WIFI antena, (g) waveguide antena, h) funnel antena, (i) loop antena, (j) MRI antenas, (k) frame antena, (l) MEG antena.

matching. Just behind the funnel, there is a voltage probe with a connector for joining a coaxial cable.

Another type is a loop antenna, figure (i), in which a voltage is induced, due to a change of the magnetic flux of the wave. A suitable capacitor connected to the antenna tunes resonance of the antenna, and thus maximum efficiency of detection. In figure (j) is the detection antenna of MRI (*Magnetic Resonance Imaging)* devices. Figure (k) shows a simple table frame antenna. Devices for measuring the body's magnetic manifestations, such as MKG (*Magneto Cardiography*), MMG (*Magneto Myography*), and the like, also use detection coils. Figure (l) shows a MEG (*Magneto Encephalography*) device, which serves for the examination of brain currents. The figure shows a headpiece with 275 sensors based on detection coils.

A common feature of antennas is the sensitivity to the polarization of the EM wave. The electric dipole antenna is sensitive to waves polarized in the dipole direction. Similarly, the loop antenna is sensitive to the magnetic field perpendicular to the loop.

The induced voltage U occurs at the output of the antenna. This voltage proceeds via a connecting line to the receiver, which processes it in the demanded manner. The amplitude, frequency, and phase of this voltage correspond to the same quantities of the wave. In this way, it is possible to sense the amplitude, frequency, phase, or pulse modulation of the wave, and to detect the information carried by the wave. A typical example from biomedicine is the detection of an FID signal in the magnetic resonance device.

1.7.1.2 Optical detectors

The optical radiation includes visible light, infrared, and ultraviolet radiation. There are two groups of detectors of optical radiation.

Detectors of the first group are *bolometers*. They measure the intensity of radiation using the change of temperature caused by the sensor heating due to the absorption of the radiation. The change of temperature is most often evaluated from a change of the electrical resistance of the absorbent body, which is, e.g., a thin platinum strip or semiconducting thermistor. A lens or mirror concentrates the radiation on the absorbing body. This body is thermally connected with the surrounding, thus creating its thermal equilibrium. The change of temperature, and thus of the resistance of the body, is directly proportional to the intensity of the incident radiation. The bolometer display is calibrated to directly indicate the intensity of the incident radiation. Due to the thermal inertia of the detection body, the bolometers are not suitable for monitoring faster changes in radiation intensity. The advantage of bolometers is that they are broadband, from radio waves to gamma radiation. Bolometers are used, e.g., in astronomy for the detection of stellar radiation, especially in the range of radio and infrared radiation. New types of bolometers with graphene (carbon nanostructure) as a detector are currently under development. In these bolometers, the incident radiation directly controls the electron gas without any mediation by the crystal lattice, which allows, in addition to high sensitivity and a wide sensitivity band, the short time constant of the order of up to picoseconds.

In biomedicine, bolometric, resp. calorimetric methods are used to control the exposure of infrared radiators. Measuring the intensity of X-rays or gamma radiation is used, e.g., in the calibration of therapeutic sources of ionizing radiation using phantoms. Bolometers also detect particle flow, e.g., in accelerators.

The second group can be referred to as *quantum detectors*. They use the quantum nature of radiation and the quantum nature of the energy spectrum of the detection substance. The most widely used are external or internal photoelectric effects. The first case represents vacuum phototube or photomultipliers, the second is semiconductor photoresistors, photodiodes, or phototransistors. In semiconductors, the incident radiation causes the excitation of pairs of electron-hole, which affects the electrical conductivity of the photoresistor, or the closing current of the PN passage. Due to the lower cut-off frequency of the semiconductor detector, which is given by the width of the forbidden bandgap, these detectors are not sensitive to low-frequency (thermal) noise. They are used to detect optical radiation (infrared, visible, and ultraviolet).

Special cases of semiconductor detectors are the CCD and CMOS structures. They are photodiodes, arranged in a chessboard grid on the surface of the microchip. Due to illumination, the elements of the chip accumulate the charge, which is then electrically scanned. Each element (pixel) is assigned a voltage value, which is then digitized and stored in the device's memory. There are three sub-grids on the chip, every with sensitivity to different R-G-B colors. There is imaging, due to the ratio of intensities of the light components R-G-B, any observed color. In this way, the device's memory stores complex information about the color image. Digital cameras and camcorders use these CCD or CMOS sensors. CCD sensors are most used for cameras to capture a color image in the visible region of the spectrum. CMOS sensors, which are faster and have lower noise, are mainly used for fast sensors (camcorders) and in the field of infrared (thermal) radiation imaging

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cameras. CMOS sensors integrated with signal amplifiers and a microprocessor are advantageous in the case of compact systems such as photo cameras in mobile phones.

1.7.2 Photomultiplier

Special electronic detectors—photomultipliers are used to detect very low-intensity optical radiation.

The principle of the photomultiplier is in **Figure 17**. The detected radiation (also the only photon) incidents on the photocathode PK. If the photon energy is greater than the edge emission energy of the electron from the photocathode, the electron is released. In an electric field with a voltage U_1 between the cathode and the first electrode D1 (dynode), the electron accelerates, and due to impact on the dynode D1, it causes the emission of several secondary electrons (secondary emission). The secondary electrons are accelerated by the voltage between the first, second, and other dynodes, and after every impact, again cause secondary emission of other upright brackets (k) electrons. In this way, the number of electrons gradually multiply, and after the impact of k^n electrons on the last electrode A (anode), arises an output current pulse in the anode resistor. This pulse is large enough to be detected by a pulse counter connected to the photomultiplier. This achieves an amplification of the number of electrons up to 108. Photomultipliers also have low noise. They are also able to detect individual photons, hitting the photocathode.

Photomultipliers are used in astronomy to detect very low radiation from distant stars, to detect very low biosignals emitted by living organisms and the like. The use of photomultipliers in ionizing radiation detectors is significant.

1.7.3 Detectors of ionizing radiation

The spectrum of electromagnetic waves also includes ionizing radiation (UV, X, gamma), which is used in radiation diagnostics (skiascopy, CT, nuclear methods—gamma camera, PET, SPECT).

For high-energy X or gamma photons, the direct photoelectric effect has low efficiency. Therefore, ionizing radiation is first transformed into an optical one. For this reason, serve *scintillation crystals*, especially Na I, Cs I, Ba F_2. After

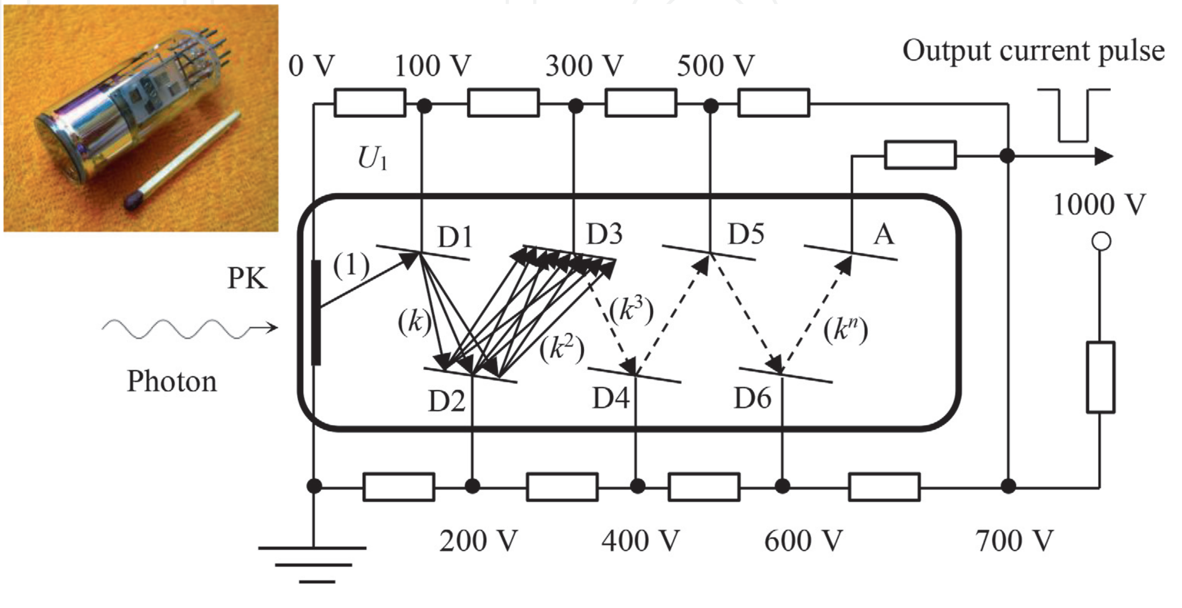

Figure 17.
Photomultiplier scheme.

irradiation with high-energy photons, electrons are excited from deep electron levels to excitation levels, from which the electrons relax to lower levels gradually (in smaller steps). It gives rise to photons with lower energy from the optical band. It represents a quantum transformation of the energy of photons from the X or γ bands to the optical one, where they can be detected by optical photodetectors. Since the probability of capturing high-energy photons is small, a sensitive detector (photomultiplier), is used to detect secondary optical photons.

Figure 18 shows an ionizing radiation detector. It consists of a matrix of individual detection cells. Each cell contains a collimator C (lead tube), which ensures that only photons 1 fall from one direction on the scintillation crystal SC. Photons 2 inclined obliquely, are captured on the walls of the tube. This ensures the directionality of the detector. The detecting cell thus determines the direction of the point of the radiation source. The cell matrix creates an area detector that scans a certain part of the body at once. Behind the scintillation crystals is a set of photomultipliers PM, from which the signals go to a computer. Scintillation detectors allow detecting X and γ rays in CT scanners, gamma cameras, PET, and SPECT scanners.

In **Figure 18** on the right, is a diagnostic *gamma camera,* which is investigating the distribution of a radioactive substance (radiopharmaceutical) in the body of the examined patient. A radiopharmaceutical is a source of radioactive gamma radiation emitted from the body. The two detection cameras are opposite each other in a rotating holder. The detection matrix only determines the direction of the place from which the radiation comes. However, if record a signal from different directions of camera rotation, it is possible to accurately determine the location of the radiation source by computer reconstruction.

In addition to scintillation detectors, ionization chambers are used to detect ionizing radiation. They utilize the ionization of the low-pressure gas in a tube, in which the release of the electron causes an electric current pulse. A typical instrument is a *Geiger-Müller counter* used for measuring the radioactivity of the environment.

The photographic dosimeter is another type of device for measuring the accumulated irradiation. The incident radiation activates the photosensitive film, and after the film developing the murkiness of the emulsion determines the radiation dose.

Another type of personal dosimeter is a *thermoluminescent dosimeter*. It is a semiconductor detector with a metastable excitation level with a long relaxation time. Due to the irradiation, electrons are excited to a metastable level and remain

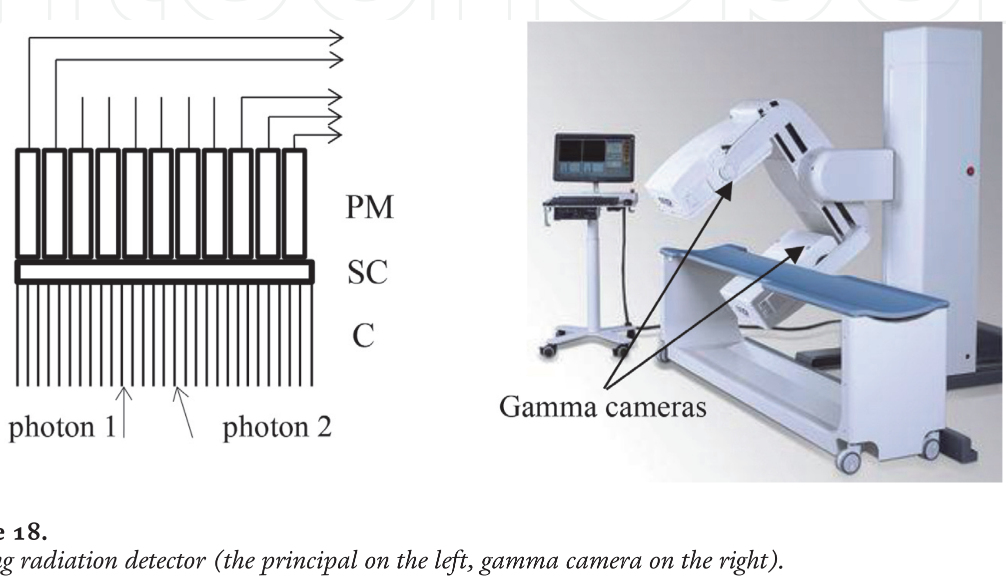

Figure 18.
Ionizing radiation detector (the principal on the left, gamma camera on the right).

there for a long time. The number of accumulated electrons is directly proportional to the irradiation. After heating the irradiated detector, the electrons relax to the ground state and emit photons with an energy equal to the energy of the electron transition. The emitted photons are detected, e.g., with a photomultiplier. The obtained photoelectric signal is directly proportional to the absorbed radiation dose. Crystals of Li F, Ca F_2, Mg Be O_4, and others for various types of ionizing radiation are proper, as materials for thermoluminescent dosimeters.

1.8 Perception of light by the human eye

An important source of information is for people the sight, which is the electromagnetic channel of direct communication between the world and a man. It involves the reception, processing, and evaluation of electromagnetic waves in the frequency range of visible light. The vision system consists of three parts. The first one is the optical processing of the incident wave, the second the detection part, and the third the processing of the detected information in the brain. In the wavelength band of approximately (380–780) nm, or the range of frequency of (385–790) THz, detects the eye EM waves (visible light) and transmits a signal through the optic nerve to the center of vision in the brain.

1.8.1 Optical system of the eye

The eye as a sensor processes light incident on the system of light-sensitive cells on the retina of the eye. The optical system of the eye ensures the creation of a real image of the observed object on the retina. The structure of the eye is in **Figure 19**. The functional parts of the optical system are the cornea, anterior chamber, lens, and vitreous body. As we can see in the picture, it is a convergent optical system, whose task is to display a beam of rays emanating from a certain point of the object to one point on the retina. The main parts important for the projection of the observed object on the retina are the lenticular anterior chamber closed from the outside by the cornea, the ocular lens with variable optical vergence by clamping on the ciliary body, and the liquid vitreous transmission medium. The total optical vergence of the eye is approximately 60 D (dioptres), of which only 20 D falls on the ocular lens. The diameter of the eyeball is 24 mm, the distance between the lens and the retina is approximately 17 mm.

When the lens muscles are completely relaxed, the lens shrinks and has maximum vergence. In this case, the object sharply displayed on the retina is at a minimum distance, called a *nearby point*. For the normal eye, it is about 10 cm. It grows with age up to 50 cm at the age of about 50 years. When tensing the lens muscles, the maximum flattening of the lens occurs. In this case, the eye focuses on the retina object at the maximum distance, called a *distant point*, ideally at infinity. Accommodation of the lens at the age of about 15 years, has a range of about 10 D. At a later age over 50 years this range is only 2 D, and at the age of 70 years, the ability to accommodate the eye completely fades. The distance of the object at which the young eye least strains by accommodation is the so-called *conventional optical distance,* approximately $l \approx 25$ cm.

If the eye is not able to focus close objects on the retina (focus is behind the retina), **Figure 19**, the eye is farsighted (hyperopic eye). This error is corrected by spectacles or contact lenses with positive optical power (converging). If the eye is short-sighted (myopic eye), the distant objects focus in front of the retina, and this error corrects diverging glasses with negative lens power. At present, there are surgical procedures, which allow modifying the lens or cornea with a laser so that it is not necessary to use glasses. Today's ophthalmic optics offer various convenient vision

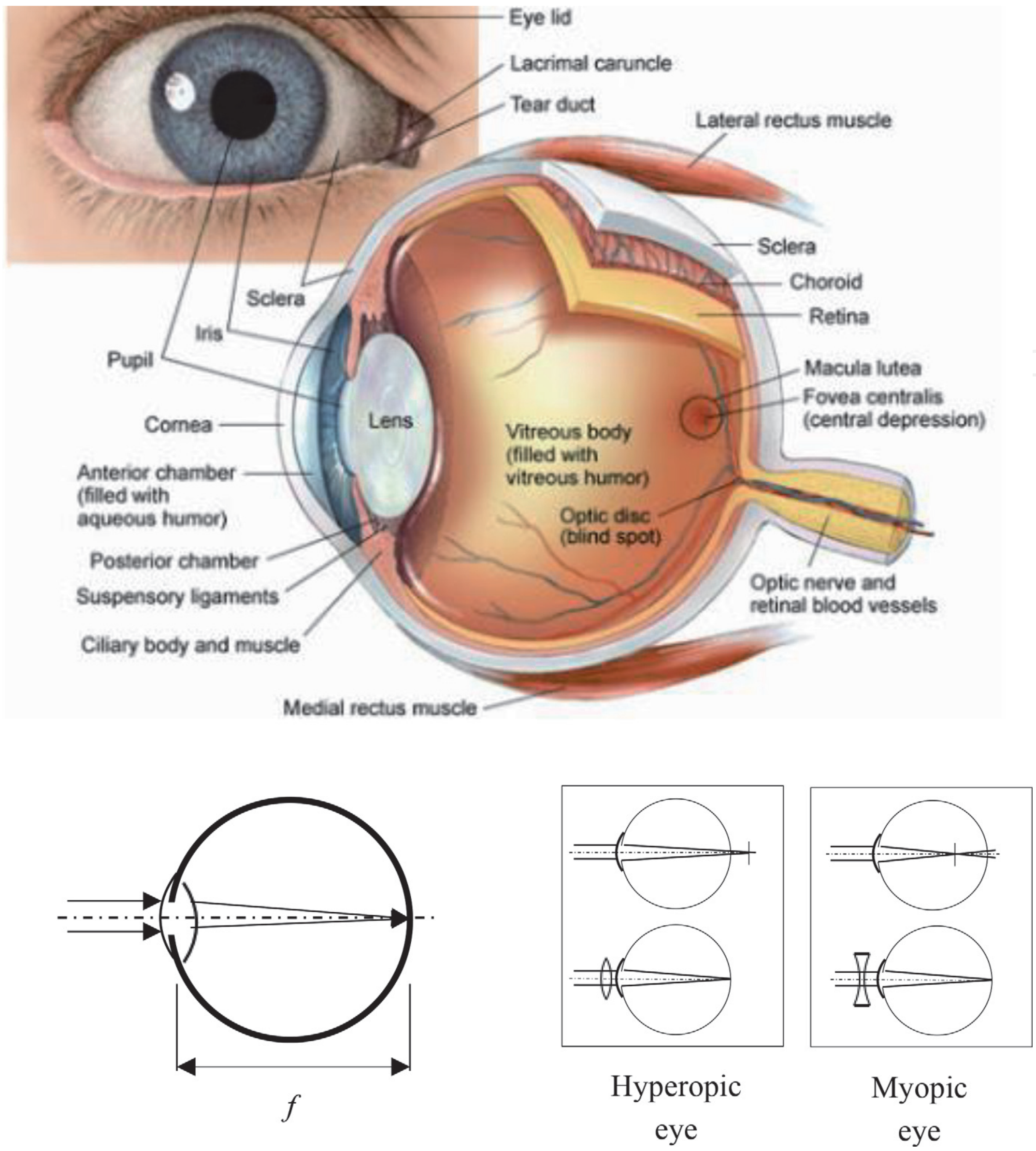

Figure 19.
Eye and optical eye defects.

correction aids, such as bifocal or multifocal spectacles, spectacles responding to light intensity (helio-variable), which are obscured by the incident radiation, spectacles with a UV filter, which protect the eyes from the harmful UV radiation, etc.

1.8.2 Light detection by eye

Light detectors are cells on the retina of the eye. There are four types of cells for vision. The rods are broadband, do not distinguish colors, and are sensitive to the wavelength band (380–650) nm with a maximum sensitivity at the wavelength of 500 nm. The cones are narrowband. There are three species with maximum sensitivity in the wavelength bands (440–450) nm (blue), (535–555) nm (green), and (570–590) nm (red). Light with wavelengths shorter than 380 nm (ultraviolet) absorbs the lens and does not hit the retina. With sufficient intensity, the eye perceives light up to a wavelength of 780 nm.

There are 5–7 million cones, and they are concentrated mainly around the yellow spot (a retina point on the optical axis of the eye). For the best color vision, you need to look directly at the object. The rods are 120 million and have the highest density at an angular distance of 25° away from the axis. For night vision, it is necessary to look at an angle of approximately 25° away from the object (so-called *side vision*) for the best sensitivity. The blind spot, where are no light-sensitive cells, is approximately 20° away from the axis towards the nose. It is the output of the optic nerve.

Color-photopic vision (cones—contain the photosensitive protein photopsin I, II, III) has a total wavelength range of (430–690) nm at the level of sensitivity drop to 1% (−20 dB) with a maximum at 555 nm (yellow-green color), **Figure 20**.

Night (black and white)—scotopic vision (rods—contain the photosensitive protein rhodopsin) has a wavelength range of (380–650) nm with a maximum at 500 nm. The eye can distinguish two colors with a wavelength difference of 1–2 nm (up to 160 colors) and up to 600 thousand shades.

As the light intensity decreases, at first the red, then blue, and finally the green cones, are gradually eliminated. Therefore, in the gloom, the scene color turns to blue-green or green.

The eye adapts to darkness in approximately 10 min (complete adaptation lasts up to 1 h). Back adaptation to light takes 2–3 min. This is the essence of the vision loss of a driver due to bright headlights at night. At low light intensity, the red cones stop working, but the green and blue remain active. If we want to illuminate something and not lose adaptation to the dark, we use red lighting.

From each cell on the retina comes a nerve fiber that conducts excitement into the brain. Close to the yellow spot, each cell has its fiber. At the edge of the retina, there are more cells connected to one fiber. Therefore, the best resolution is around the center of the retina. All fibers together form the optic nerve, which contains approximately 1 million fibers. The optic nerve originates in the eye around the blind spot, in which are no light-sensitive cells.

The angular resolution (lateral) is 1′ (angular minute) and is given by the density of the cones in the yellow spot. Due to the diffraction of light on the pupil, the resolution angle increases (**Figure 21**).

Retinal cells are characterized by the logarithmic dependence of the output signal on the intensity of illumination. Thanks to this, the eye has a huge range of brightness resolution—up to 10^{12}, i.e., 120 dB, from the smallest values of 10^{-6} cd·m^{-2} to 10^{6} cd·m^{-2}. Photopic vision requires a light intensity >3 cd·m^{-2}, scotopic <3 mcd·m^{-2}, see.

In addition to visual perception, the retina of the eye has another function. There are other Non-Images Forming Photoreceptors (NIFPs—contain the photosensitive

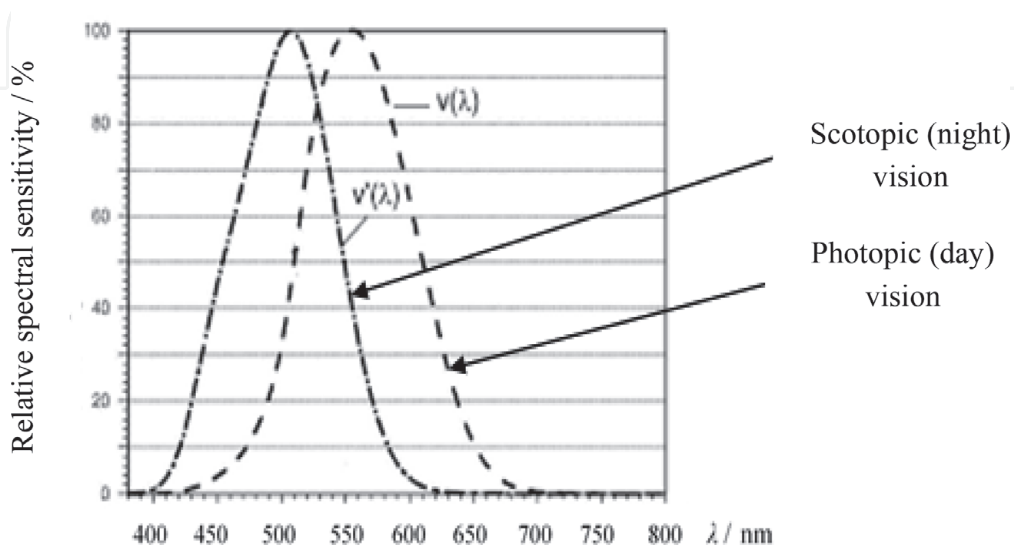

Figure 20.
The curve of relative spectral sensitivity of the eye in day and night vision.

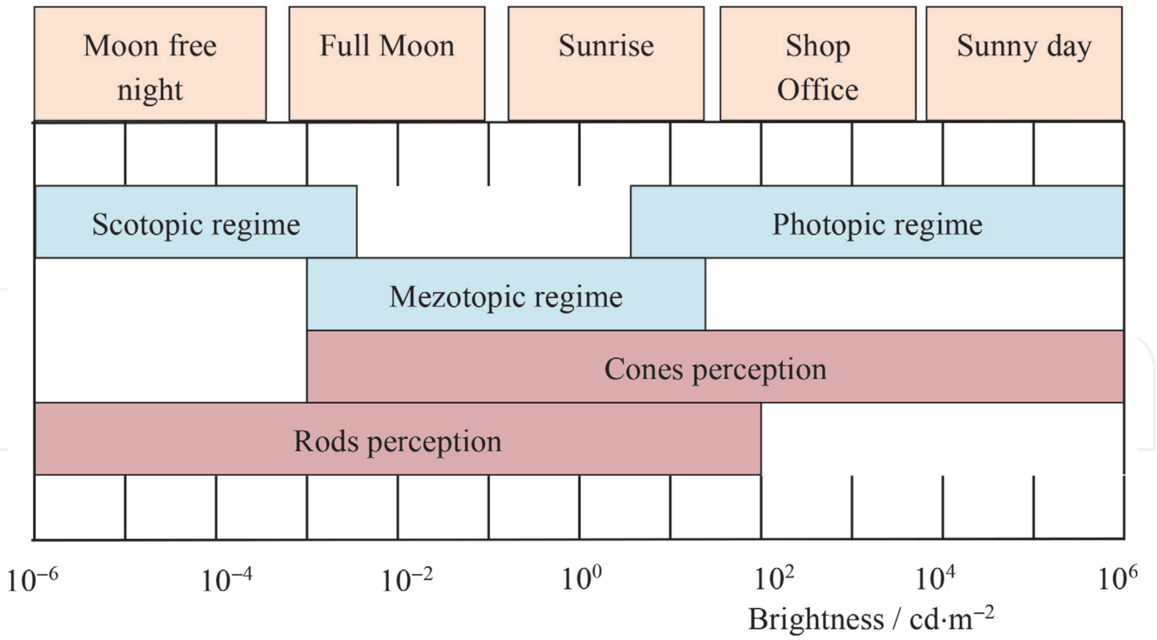

Figure 21.
Perception of objects with different brightness by different cells.

protein *melanopsin*) on the retina that does not participate in imaging. Their signals go to the pituitary gland, which controls the pineal gland, which produces melatonin, a hormone that affects sleep rhythm, and a variety of physiological functions. The spectral degree of suppression of melatonin production is shown by a graph of the *meltopic spectrum*, **Figure 22**. As we can see, blue light suppresses melatonin production the most. Melatonin regulates sleep and the sleep cycle. Sleep, e.g., does not affect red light (above 600 nm). If we do not want to disrupt melatonin production and thus sleep at night, it is advantageous to use red lighting. Blue, on the other hand, severely disrupts sleep and is used when the sleep cycle needs to be regulated. In some cars, dim interior blue lighting can be observed at night, which should have a positive effect on keeping the driver's attention while driving at night.

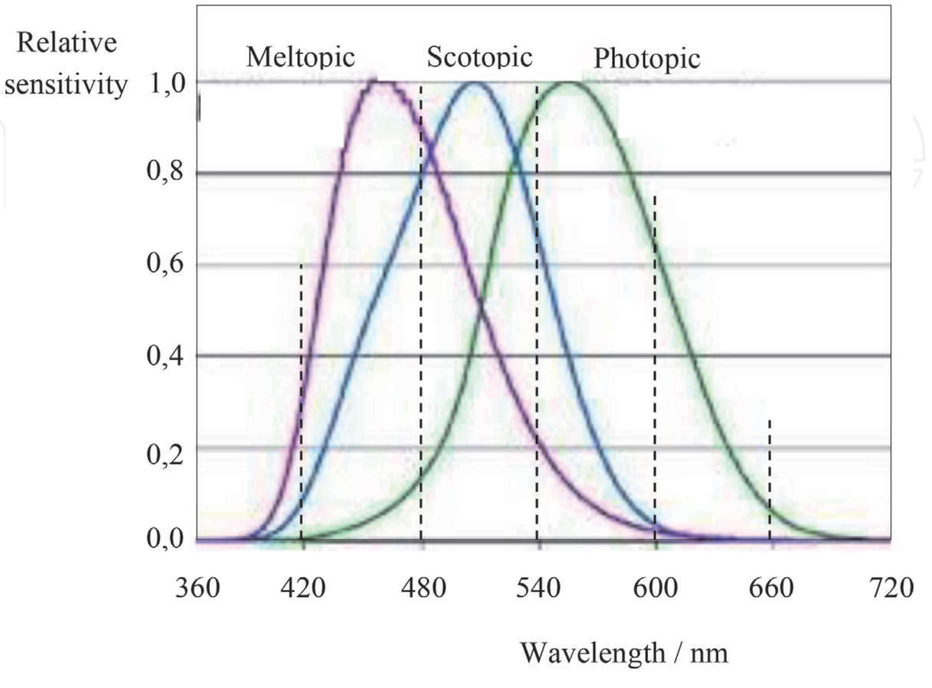

Figure 22.
Three types of eye sensitivity spectra.

1.8.3 Optic nerve signal processing in the brain

Visual perception does not arise in the eye but in the brain, where the signals of nerve fibers from both eyes terminate. After processing these signals, a spatial and color image of the object creates in the brain. During processing, the brain also uses the previous experience stored in memory and corrects some shortcomings of the received signal. For example, we can read fluently a text with errors or shuffled letters. There also arise various optical illusions. The image on the retina projected by the eye lens is inverted, but we perceive the image created in the brain as straight. There are experiments, in which the scene was turned over by special glasses. In a relatively short time, however, the normal straight view renewed again. The brain reacted and based on experience, turned over the perceived image in the brain. After taking off the glasses, one observed for some time the surroundings overturned back to the normal view.

1.8.3.1 Three-dimensional vision

One can see the scene spatially (3D) when one perceives not only its right-left sides but also its depth. This is due to a pair of eyes that are 6–7 cm apart from each other. It provides slightly different images of eyes when observing, especially near objects. The right eye sees more of the right side and left more of the left side. The synthesis of these images in the brain forms a *stereo-effect (or 3D effect)*.

To see a three-dimensional image, we must provide both eyes with corresponding images. There are several ways to do this. The first one uses the recording of both images for the left and right eye in two complementary colors and composing them into one resulting image. If looking at the resulting image by glasses with corresponding color filters for each eye, every eye perceives its image. Stereo television utilizes another system. Both images are sent alternatively with two polarizations, mutually perpendicular, and the viewer observes the TV screen by glasses with corresponding polarization filters. The next system quickly alternates both images for the right eye and the left eye on the monitor, and the observer uses electronically controlled glasses, transparency of which synchronously switch-over for the right eye and the left eye.

An example of the extraordinary ability of the brain, is the so-called *stereogram,* **Figure 23**, in which the views of both eyes are mixed into one planar image. If we look at the picture and try to accommodate the eyes to infinity, a three-dimensional object will emerge from the stereogram in a short time (you should see a wolf in the forest with spatially arranged trees in the foreground and the background). The condition is to see with both eyes, if you use glasses, also with glasses. The brain can classify seemingly chaotic pictures and create a meaningful interpretation of the signals captured by the eyes. It selects information from the image, separately for the left eye and the right eye, and creates the resulting 3D image.

1.8.3.2 Holography

In many cases, the spatial (3D) representation of objects requires, whether for scientific purposes, for demonstrations, or to archive records. 3D imaging is one of the modern trends in biomedicine.

Within 3D imaging, the name *holography* (Greek: *holos*—complete) mentions as creating a complete image of an object. 3D perception is created in the brain by processing the signals of the optic nerves of the right and left eyes, which differ slightly. If we want to display an object so that we can see it spatially, we must

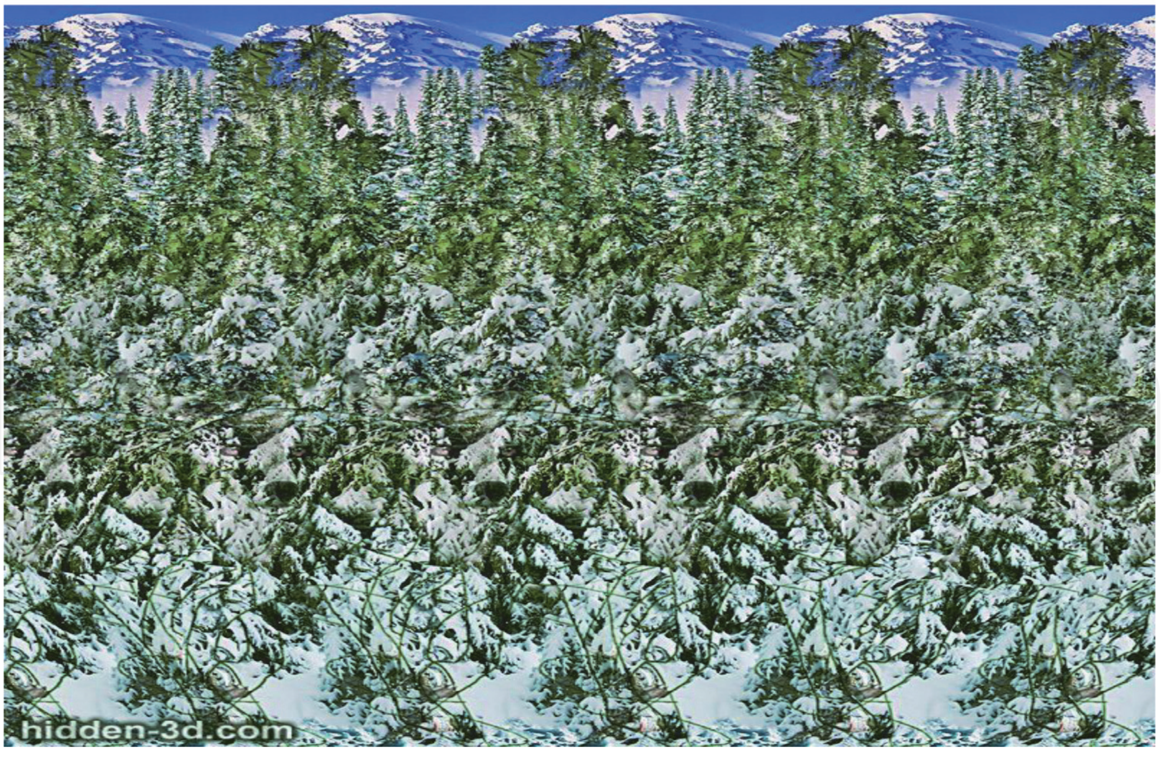

Figure 23.
Stereogram (wolf in the forest).

reproduce the original wavefield emanating from the object. The basic idea of the record is as follows, **Figure 24**.

If we illuminate the object (R1 rays) from the source S1, we see the original object, observing the reflected or scattered light (rays R2). Then we replace our eyes with a photographic plate H1. With the help of a semi-transparent mirror SM, we illuminate the plate with reference light (rays R3 emanated virtually from the virtual image VS1). The rays R2 and R3 interfere at the surface of the plate, and we record the interference maxima of light intensity by blackening the photographic emulsion. The recorded interference picture is the hologram H2. To create a static interference pattern, the light source must be coherent. The LASER is, therefore, necessary for recording and reconstruction of the hologram.

If placing the obtained hologram H2 in its original position and illuminating with the reference beam R3 the same as at recording the hologram, light diffraction on the hologram occurs. The 1st order diffraction (R4 rays) is a very reproduction of the original wavefield from the original (R2 rays). The eyes thus persist the field created by imagining an apparent image in place of the former original, as if observing a real original. Since it is a matter of creating a complete field of light (*holos*), the image has the properties of the original. It means the eyes perceive the image spatially.

The image can be viewed from different angles, as the size of the hologram plate allows. Such a hologram is often fully sufficient to replace a valuable original, e.g., exhibited in a museum, as the visitors observe it only from a limited range of angles. However, this type of hologram does not allow you to observe the back of the object. It only shows the visible front surface of the object. It also does not allow us to view the inside of the object.

Current tablets and smartphones with LCDs allow the projection of spatial images and 3D videos, using Pepper's "*Ghost effect*"—PGE, **Figure 25**. To view the subject from different sides in the plane of the screen, four images are created instead of two, which are saved in the computer's memory. LCD projects these

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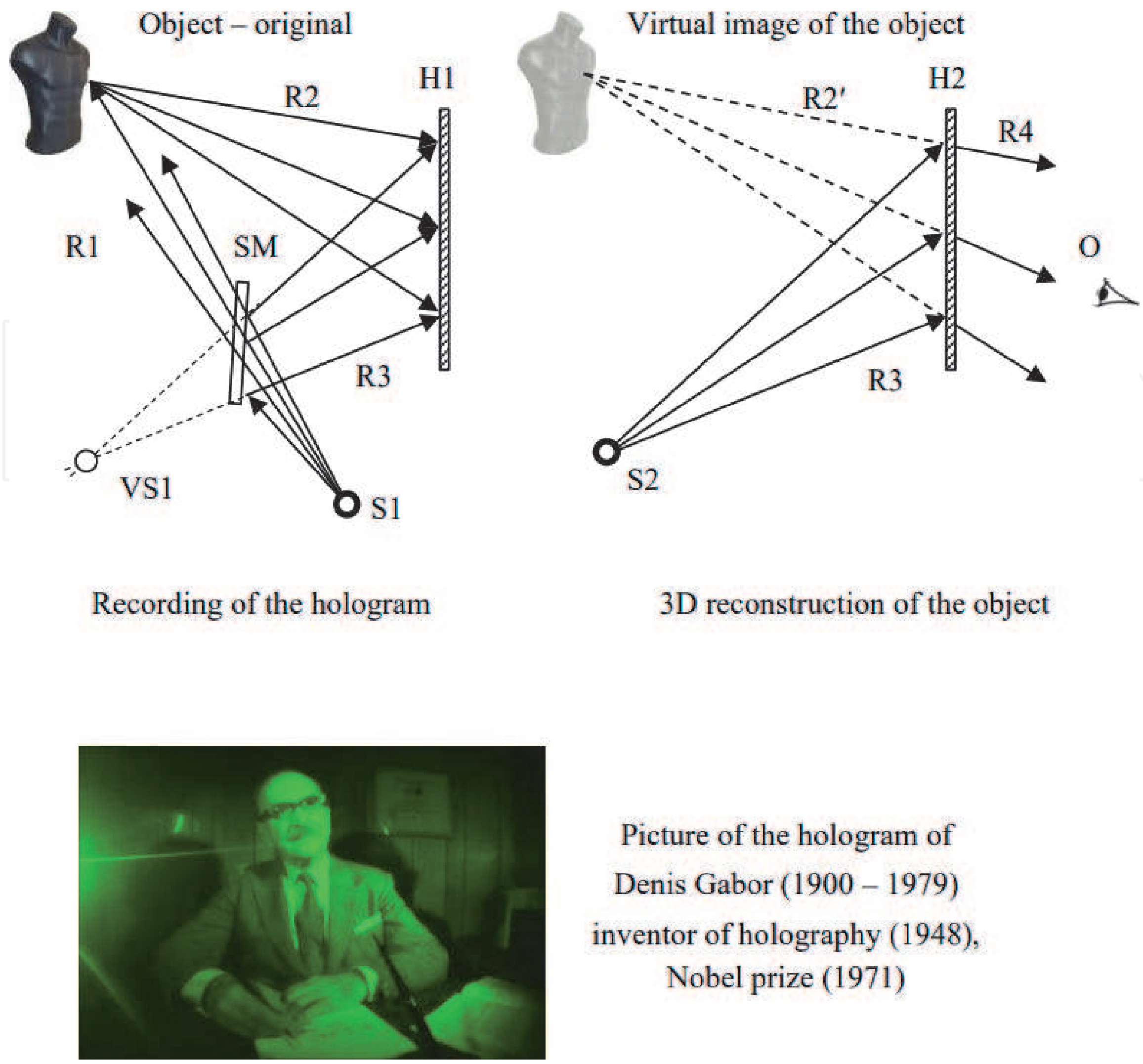

Figure 24.
Hologram recording and reconstruction.

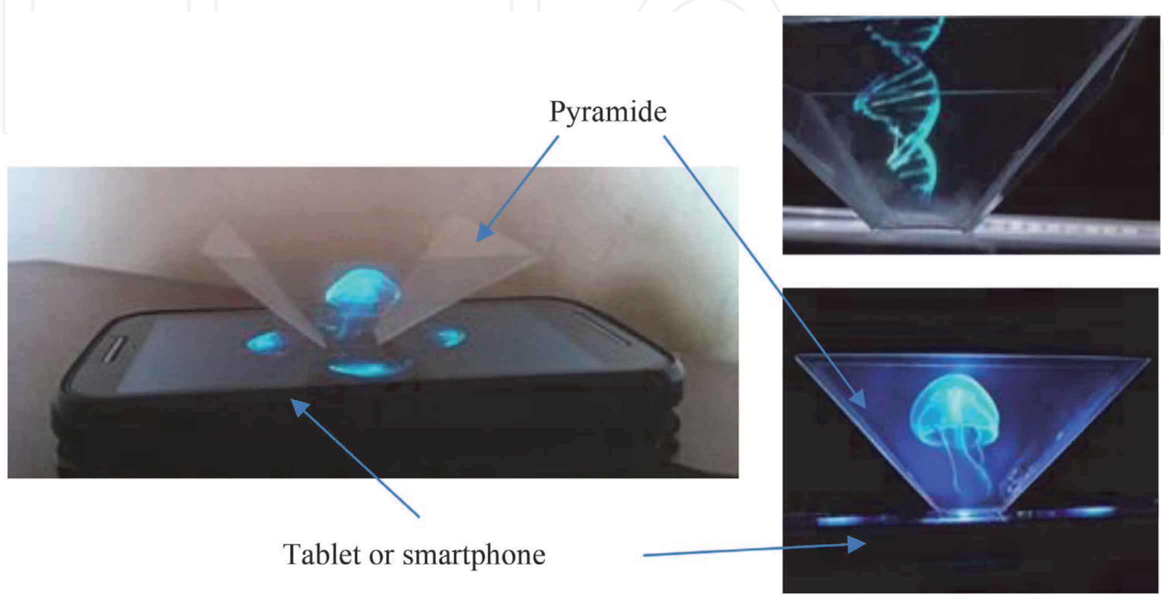

Figure 25.
Holographic display using PGE (pepper ghost effect).

images onto a pyramid, made of a special foil with an angle of inclination of 45° to the display.

The observer looks at the pyramid parallel to the plane of the display. He perceives four images created by the reflection of the displayed image on the walls of the pyramid. Each eye thus gets different images to create a stereo effect. From any angle, the observer sees the 3D image of the projected scene. The described system allows seeing a stereo video using personal electronic devices. Medicine and biochemistry use this method of spatial imaging for imaging body organs, cells, macromolecules, etc., especially for study purposes.

1.8.3.3 Virtual reality

3D vision arises if each eye receives a correspondingly different image. This also achieves using special spectacles with displays for each eye connected to a computer.

The digital model of the object is stored in the computer storage. Proper software creates signals corresponding to the demanded view of the object for each eye. One's sight then perceives a 3D image of an object, referred to as *virtual reality*. Computer software allows manipulating the object view. Virtual reality is widely used, in biomedicine, e.g., in teaching anatomy. The computer stores a model of the body with all the details, e.g., obtained from CT or MRI tomographic scanners. The software allows us to display separately individual organs, skeleton, blood circulation, muscles, etc., see.

The spectacles may be opaque, and then the observer only sees what is projected. They can also be semi-transparent, and then the observer sees the surrounded space, together with the 3D image of the object projected into this space. The spectacles have position sensors wirelessly connected to the computer so that the computer can create views from different angles and positions. Virtual reality finds application in the entertainment industry, but also in science and education. The computer allows you to create moving images, so you can project entire movies with these spectacles. Virtual reality is one of the modern trends in medicine. It especially uses databases from tomographic examinations, i.e., information databases not only about the surface but about the entire volume of the displayed object. Modern projection, as well as communication technology, enables the realization of a virtual keyboard and a "virtual cursor" with which the observer can remotely control a computer with a finger or a special pen, shoot the virtual image in various ways, make cuts, select details from the image, e.g., separate the muscles, vascular system, skeleton, select the operated organ, etc., from the body.

It is possible to connect multiple spectacles to a computer, so, e.g., the whole operating team observes the same virtual image, and during the operation, it can use the display of the operated organ, see. Virtual reality offers unsuspected possibilities, and its use will rise soon (**Figure 26**).

1.8.3.4 Tomography

Tomography is a modern method of complete 3D imaging and relates to the use of computers. The spatial object is scanned in thin layers (*Greek: tomos—layer*). The two-dimensional images (slices) thus obtained are stored in the computer's memory. Each acquired 2D image shows the entire internal structure of the object's section. For some examinations, only 2D images are sufficient, but a series of 2D images can be composed using a computer to create a 3D image of the object. This 3D image allows observing the image of the object from different sides on the

Figure 26.
Virtual reality. Examples: https://www.youtube.com/watch?v=U–m89jv8So.

screen, just like the real object. In this way, one can create a template for virtual reality. Creating a 3D image of an object layer by layer calls *tomography*. It became possible only after the development of computers with a sufficiently high operating speed and especially with huge memory capacity. The beginnings of modern computed tomography thus date back to the 1980s.

In **Figure 27** are examples of tomographic images obtained by different imaging methods.

Other tomographic images include nuclear methods using γ-irradiation, such as PET (Positron Emission Tomography) and SPECT (Single Photon Emission Computed Tomography).

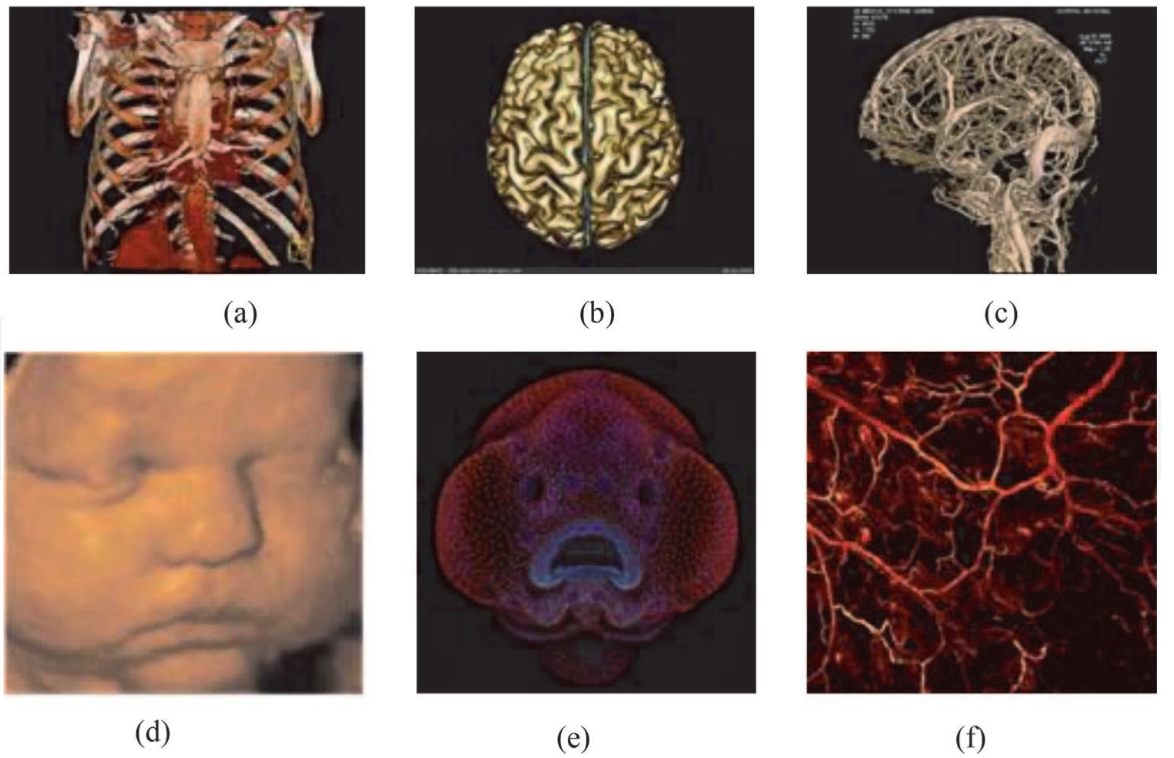

Figure 27.
Examples of tomographic images. (a) CT-Computed Tomography uses X-rays, (b) and (c) Magnetic Resonance Imaging (MRI) uses magnetic resonance imaging and RF signal FID, (d) USG (Electronic Focus Ultrasonography), (e) Confocal Laser Scanning (CLSM) Microscopy), (f) Photo Acoustic Microscopy (PAM).

1.8.4 Photometry

Most often use of light is lighting. For this reason, it is necessary to introduce physical quantities that describe the light effect of electromagnetic radiation on human vision.

In history, people used an especially made candle as the normal gauge of a point light source effect on human vision.

The accurate measurement evaluated the electromagnetic radiant power of the normal light point source of the unit luminous intensity. The light point source with the luminous intensity of 1 cd (candela) corresponds to the power of the source of thermal radiation of 1/683 W.

The current definition uses a monochromatic point source with a wavelength λ_m = 555 nm (yellow-green color), which corresponds to the maximum sensitivity of the eye in photopic (daily) vision. The luminous effect describes the quantity *luminous flux* Φ (λ), compared with the corresponding radiant flux Φ_e (λ). The unit of 1 lm (lumen) of the luminous flux, (incident on the pupil of the eye), is defined by the rate to the unit of 1 W (watt) of the radiant flux Φ_e (λ) by the relation, which respects the old definition of the candle.

$$\Phi\,(\lambda_m) = K_m\ \ \Phi_e\,(\lambda_m), \text{where } K_m = 683 \text{ lm W}^{-1}. \tag{75}$$

If we use monochromatic light with a different wavelength λ, the luminous effect of the radiation describes the luminous flux

$$\Phi\,(\lambda) = K(\lambda)\,\Phi_e\,(\lambda) = K_m\ \ V\,(\lambda)\ \ \Phi_e\,(\lambda), \tag{76}$$

where K (λ) is the *spectral sensitivity* of the eye to light of wavelength λ, and V (λ) is the *relative spectral sensitivity* to light of wavelength λ. The dependence of V (λ) on the wavelength for photopic vision is in **Figure 28**.

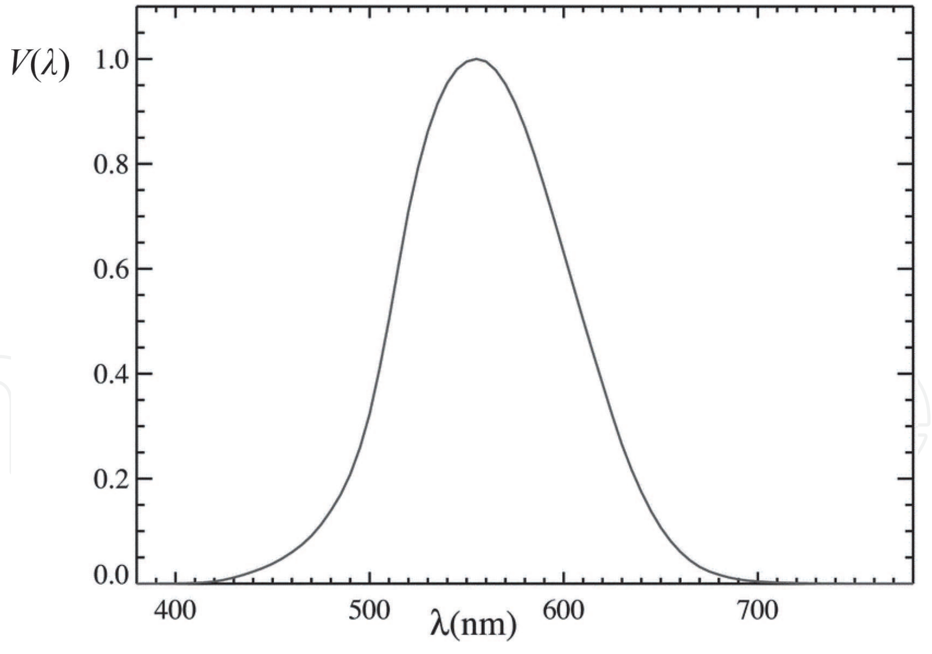

Figure 28.
Relative spectral sensitivity of the eye in photopic vision.

In the case of polychromatic light, the total light effect is equal to the integral light effect of all wavelengths

$$\Phi = K_m \int_0^\infty V(\lambda)\ \Phi_e'(\lambda)\ d\lambda, \tag{77}$$

where $\Phi_e'(\lambda) = \frac{d\Phi_e(\lambda)}{d\lambda}$ is the spectral density of the radiant flux [W m^{-1}].

The luminous intensity I of a point source is then defined by the luminous flux Φ radiated into a unit solid angle (1 sr).

$$I = \frac{d\Phi}{d\Omega}, \text{the unit } 1\ \text{cd} = 1\ \text{lm} \cdot \text{sr}^{-1}. \tag{78}$$

When using a lighting source, we are interested in what lighting of the object will cause the source. The quantity of *illuminance* is defined by the luminous flux incident from the source on a unit area perpendicular to the direction of light propagation

$$E = \frac{d\Phi}{dS}. \tag{79}$$

The unit of illuminance is 1 lx (lux) = 1 lm m^{-2}.

We measure the illuminance with a Lux-meter, (e.g., an application in a smartphone). It is easy to make sure that with increasing distance r from the source, the illuminance decreases, and depends on the angle ϑ of incidence of light on the surface

$$E = \frac{d\Phi}{dS} = \frac{I\, d\Omega}{r^2\, d\Omega / \cos\vartheta} = \frac{I}{r^2}\cos\vartheta. \tag{80}$$

As can be seen from (80), the illuminance decreases with the square of the distance.

When evaluating surface light sources, the brightness is described by the quantity of *luminance* (the unit 1 $cd{\cdot}m^{-2}$)

$$L = \frac{\mathrm{d}I}{\mathrm{d}S_{\text{source}}}, \tag{81}$$

where d I is the luminous intensity of the elementary surface $\mathrm{d}S_{\text{source}}$ of the source.

Note. 1: At present, there are modern LED lights. On the box of the LED bulb, we can read wattage 15 W, luminous flux 1320 lm, equivalent to the luminous flux of a classic bulb with a wattage of 100 W. If the bulb emitted only light with a wavelength of about 555 nm, the corresponding luminous flux would be 100 W × 683 lm/W = 6.83 × 10^4 lm. If the equivalent luminous flux is 1320 lm, the luminous efficacy of the lamp is 2%. This is because the bulb emits most of its energy in the infrared (thermal) range, while the LED bulb emits only visible light. The energy-saving when using an LED bulb instead of a conventional filament bulb is (100–15 W)/100 W = 85%.

Note. 2: The hygienic standard for workplace lighting is at least 200 lx. The classic 100 W bulb at a distance 2 m provides illumination of 35 lx. The illuminance at night at the full moon is 0.24 lx, during the day with cloudy skies up to 3000 lx and on a sunny summer day up to 100,000 lx.

Note. 3: The human eye can distinguish a source with a minimum brightness of up to 10^{-6} $cd{\cdot}m^{-2}$.

A detailed description of photometric quantities and various light sources is provided by the physical discipline—*photometry*.

1.8.5 Colorimetry

A man distinguishes approximately 160 colors and up to 600,000 shades by photosensitive sensors for only three colors (Red-Green-Blue) and gray. All the remaining colors and shades are created by composing signals from these sensors in the brain. Just as the eye decomposes any color into three color components (signals), and the resulting color reconstructs in the brain. It is possible to create any other color from the three basic color components. This illustrates the diagram in **Figure 29**—*chromatic diagram*, or *colorimetric triangle* (*chroma lat.—color*). The colors perceived by the eye are closed in the area bounded by the contour line, on which there are monochromatic (rainbow) colors with the specified wavelengths from violet (340 nm) to red (700 nm). All colors from the marked area can be created by adding three basic colors.

The eyes use three monochromatic colors from the contour line. For sufficient coverage of the color scheme, however, three technical colors marked in the scheme on the vertices of the triangle R, G, B are sufficient. This covers the area of colors limited by this triangle. If we want, e.g., to create the color indicated by the point F in the diagram, the lines FR, FG, FB indicate the necessary light intensities of the primary sources to produce the desired color. It is not possible to create a color from outside the RGB triangle in this way. The diagram shows that by composing the basic colors in a suitable ratio $r: g: b$, a white color W arises. Monochromatic colors do not occur on the line BR—these represent *purple* colors and are composed of blue B and red R colors. Adding color to the base color sources is called *additive mixing.* This is, e.g., how works LED with electric color creation. Such LED contains three LEDs on one chip with three basic colors and independent power supplies. By changing the current of the individual segments, it is possible to change the color of the light in the range of the colorimetric triangle (**Figure 30**).

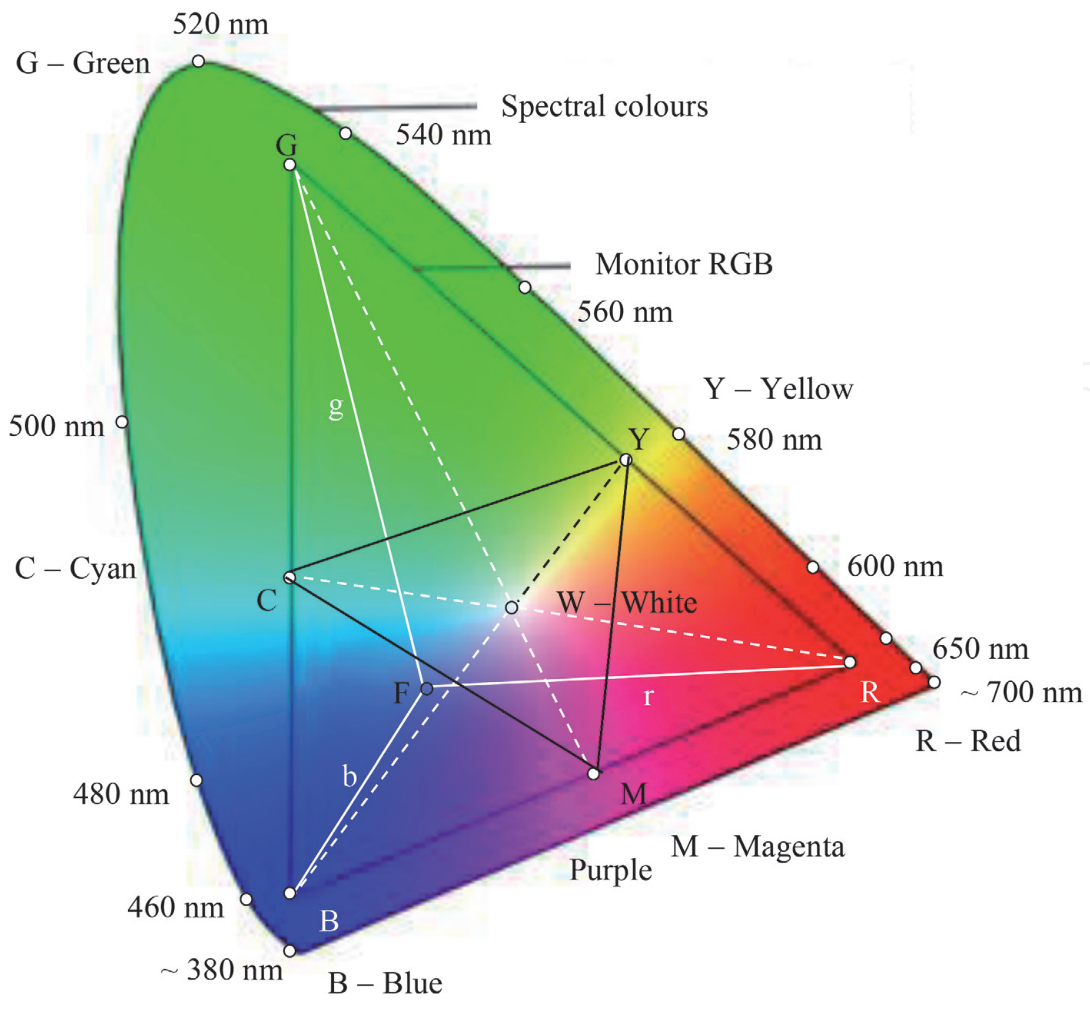

Figure 29.
Chromatic diagram (colorimetric triangle).

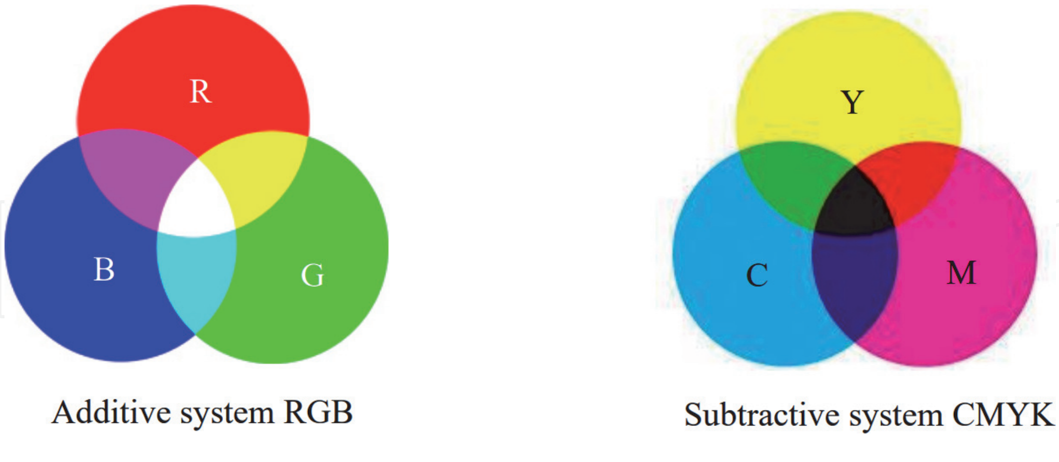

Figure 30.
Additive and subtractive color composition.

Another example is LED monitors for TVs or computers. On the monitor surface, there are three sub-grids with LEDs of three basic colors, which are powered by a digital image signal source.

For each basic color of the triangle, there is a so-called *complementary color*. By adding the basic and complementary colors in a suitable ratio, we get white. In the diagram, the base and complementary colors are represented by points on one line at the intersections with the sides of the triangle, e.g., B-Y, G-M, R-C. To blue (B) is complementary yellow (Y-Yellow = R + G), to green (G) magenta (M-Magenta = R + B) and to red (R) cyan (blue-green) (C-Cyan = B + G)). CMY points form a triangle, and by composing these colors, you can create any color within that triangle. We see that the color choice in the CMY triangle is smaller than in the RGB triangle.

The CMYK display system (Cyan-Magenta-Yellow-Black) uses the so-called subtractive folding (the resulting color is created from white by subtracting primary colors). Dyes are applied to the white background. Dyes filter out all or part of the respective base paint. By filtering out all the primary colors with the three dyes, black remains. This method is used by inkjet or laser printers. Because it is uneconomical to use three color toners to produce black, the printers contain a separate black toner used for black and white printing. A comparison of color production by both systems is in. We see that by the additive composition of the basic colors we get white, by the subtractive composition of the basic colors we get black.

A comparison of the RGB and CMY triangles shows that the color quality of the printed images is lower than the color quality of the LED or plasma monitor images.

Author details

Ivo Čáp*, Klára Čápová, Milan Smetana and Štefan Borik
Faculty of Electrical Engineering and Information Technology, University of Žilina, Slovakia

*Address all correspondence to: ivo.cap@fel.uniza.sk

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