5. Dielectric properties of solids

Time to study: 6 hours

Objective After studying the chapter

- you will be familiar with the types of polarization of dielectrics in static and alternating electric fields
- you will get familiarized with microstructural interpretation of polarization
- you will learn to understand the relationship between material structure and optical properties of materials
- you will understand the relationship between electrical and optical properties
- you will be able to describe optical phenomena
- you will acquire knowledge about different types of dielectrics

Lecture

5.1. Polarization of dielectrics in static and alternating electric fields

In the introduction, we are going to revise knowledge of electrostatics briefly. We are going to begin with the concept of dipole and its interaction with the electric field.

Electric dipole is a set of two equal-sized charges of opposite sign, placed very close to each other (Figure 5.1).

\[ \mathbf{p} = \mathbf{Q} \mathbf{l} \]

where \( l \) a distance between charges and \( Q \) is the electric charge. Dielectric in an electric field can pose as a set of dipoles.

In addition to the external electric field, into which we put a dielectric, a different internal (local) electric field is always located inside it. These phenomena are called dielectric polarization (Figure 5.2). If there is metal in the electric field, polarization does not occur. This phenomenon is the essence of so called Faraday cage (Figure 5.3).

Let us now analyse the various types of polarization.
The electron polarization is a phenomenon where the influence of an external electric field causes deformation of the electron shell. For example, at the electric field intensity $E=10^9 \text{V/m}$, the change in the position of electrons, or possibly ions from equilibrium does not exceed the distance of $10^{-12}-10^{-14} \text{m}$. *Electron polarization is temperature independent.* After removing dielectric from the electric field, the system of charge carriers returns in a very short time $10^{-12} \text{s}$ (Figures 5.4 and 5.5).

![Figure 5.1 Model of electric dipole.](image1)

![Figure 5.2 Electric field in dielectric](image2)
In addition to the processes of polarization associated with the generation of an induced dipole moment in the substance, there are also processes related to the orientation of the existing permanent dipole moments. *It is the case of indicative polarization.*

Molecule H$_2$O forms a dipole, because the centre of gravity of $+$ charge and the centre of gravity of $-$ charge are mutually displaced.

We also know the dielectrics, in which a considerable dependence of their relative permittivity on the temperature appears in a certain temperature range.
This specificity is usually associated with their temperature approaching the temperature of the phase transition.

The electric field changes the height of potential barrier, resulting in the transfer of charge carriers to more energy-efficient locations, and thus asymmetric charge distribution – it causes *relaxation polarization*.  

*Such polarization is temperature dependent* and the relaxation time ranges between $10^{-10}$ and $10^{2}$ s and the displacement of the particles ranges between $10^{-10}$ and $10^{-11}$.

*It is characteristic of polymers but also materials with insufficiently strong ionic bonds.*

![Figure 5.5 Atom in an electric field](image)

In macroscopically inhomogeneous dielectrics, we meet with *migration polarization, i.e. accumulation of charge carriers at the boundary of inhomogeneity.*

In electrets, a polarization charge is generated as a result of suitable heat treatment at simultaneous effect of the electric field. *An electret produces a permanent electric field in its surroundings. Electret textures do not have the centre of symmetry, therefore they exhibit piezoelectric properties.*

In dielectrics with large polar groups, a change in their arrangement or orientation occurs in the case change of a change in the intensity of the electrical field. At the same time, domain walls in ferroelectrics migrate to significant distances.
The necessary crystallographic feature of pyroelectrics is the presence of polar axis, wherein the crystal does not have the centre of symmetry, so that an arbitrary pyroelectric is also distinguished by piezo effect.

Spontaneous polarization of pyroelectric is generally compensated by charges situated on its surface. If it is heated or cooled, the density of these charges changes.

In linear pyroelectrics, the size of polarization changes only if there is a change in their temperature. Ferroelectrics as a group of non-linear pyroelectrics are characterized by the fact that with them we can change the direction of the spontaneous polarization vector in a sufficiently strong electric field. Therefore, in ferroelectrics, dielectric hysteresis occurs when monitoring dependence of \( P \) on \( E \).

Next, let us summarize phenomenological relations known from the electrostatics quantifying polarization processes.

\[
\vec{E}_S = \vec{E}_0 + \vec{E}_p
\]

\[
\vec{E}_p = \frac{\sigma_p}{\varepsilon_0}
\]

\[
\vec{P} = \kappa \varepsilon_0 \vec{E}_S
\]

\[
\vec{E}_S = \vec{E}_0 - \frac{1}{\varepsilon_0} \vec{P}
\]

\[
\vec{P} = \kappa \varepsilon_0 \vec{E}_S
\]

From microscopic view, polarization is described by Clausius-Mosotti equation in the form

\[
\frac{\varepsilon_r - 1}{\varepsilon_r + 2} = \frac{Na_s}{3\varepsilon_0}.
\]

Because it applies \( n = \sqrt{\varepsilon_\mu} \)

we obtain CM equation for the refractive index, and we can see that the optical properties of materials depend on their dielectric properties and therefore it applies
\[
\frac{n^2 - 1}{n^2 + 2} = \frac{N\alpha}{3\varepsilon_0}.
\]

5.3

\[\varepsilon_r = 1 + \kappa\]

\(E_p\) - polarized field (created by polarization charge)
\(E_0\) - vacuum field (without a substance)
\(E_S\) - the actual (final) field in a substance
\(P\) is the polarization vector
\(\kappa\) is the dielectric susceptibility
\(\varepsilon\) is the dielectric permittivity tensor
\(\sigma\) is specific electrical conductivity

Specific electric conductivity is related to their dielectric constants in the relation

\[
\frac{\varepsilon_1}{\sigma_1} = \frac{\varepsilon_2}{\sigma_2}.
\]

5.4

The knowledge acquired up to now can be summarized as follows:

◆ We consider the relative permittivity of a substance and the dipole moment of the unit of dielectric volume as the macroscopic variables in the static electric field.

◆ In the alternating electric field between the vector \(P\) and \(E\), phase shift occurs, leading to dielectric losses.

◆ In the case, the dielectric permittivity appears as a complex value, and it is also macroscopic characteristics.

In the alternating electric field, between the vector \( P \) and the \( E \) phase, a shift occurs, which results in dielectric losses.

In the case, the dielectric permittivity appears as a complex value and it is also macroscopic characteristics.

Variable electrical voltage can be written in a complex form as

\[ U = U_m e^{i \omega t}, \]  \hspace{1cm} (5.5)

where \( U_m \) is the maximum voltage value and \( \omega \) is angular frequency.

\( D(t) \) is hereby also sinusoidally changing with time, but in phases, it is delayed behind \( E(t) \) by a certain angle \( \delta \). This delay, as already indicated above, is caused mainly by the fact that due to inertia and a mutual interaction of particles, the stationary value of \( P(E) \) is set for a certain delay.

Specific dielectric losses, which are reflected in the generation of heat can be determined by the equation (the following equation expresses the nature of microwave heating)

\[ p = \int E \frac{dD}{dt} dt = \epsilon_0 \epsilon \tan \delta \omega E^2, \]  \hspace{1cm} (5.6)

where

\[ \tan \delta = \sigma / \omega \epsilon_0 \epsilon_{\text{real}}, \]
\[ \varepsilon_{\text{imag}} = \sigma / \omega \varepsilon_0, \]

\[ \varepsilon_{\text{imag}} = \varepsilon_{0\text{real}} \cdot \tan\delta. \]

The frequency dependence of the individual components is shown in Figure 5.6.

Figure 5.6 The frequency dependence of a real, imaginary component of the permittivity and \( \tan\delta \)

To conclude this recapitulation, we also show the frequency dependence of the individual types of polarization in the following Figure 5.7.
5.2. Optical properties of solids

From the basic physics course we know that the light in anisotropic media spreads differently than in isotropic environment. For example, in spreading the light in the crystal of CaCO$_3$, so-called double refraction occurs when the incident beam “breaks down” into two beams with mutually orthogonal polarization (oscillation orientation relative to the direction of spread of the wave).

However, double refraction can also occur in isotropic media if “external forces” are active within them, therefore in the presence of an external electric field, an electro optical phenomenon arises, or in the presence of external mechanical stress, an elastooptical phenomenon arises; this phenomenon will be the subject of our attention in this section.

We know that the speed of light in the isotropic environment is defined by the relation

$$v = \frac{1}{\sqrt{\varepsilon \mu}} = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} \cdot \frac{1}{\sqrt{\varepsilon_r \mu_r}} = \frac{c}{\sqrt{\varepsilon_r \mu_r}} = \frac{c}{n},$$

where $\varepsilon_r$, $\mu_r$, $c$ represent the successively relative permittivity, the medium relative permeability and the speed of the light in vacuum. It is also known that $n = \sqrt{\varepsilon_r}$ applies, because for the transparent materials it applies that $\mu_r = 1$.

The so-called optical indicatrix defined for the isotropic environment by the relation

$$\frac{x_1^2 + x_2^2 + x_3^2}{\varepsilon_r n^2} = \frac{x_1^2}{n^2} = 1$$

or in a shortened form $Bx_i^2 = 1$, where $B = 1 / \varepsilon_r$ represents a spherical surface.
Dielectric properties of anisotropic materials are described by *piezo-optic tensor* $\varepsilon_{ij}$ or inverse tensor $B_{ij}$, which is also called *optical impermeability tensor*. Optical indicatrix can also be expressed in the form $B_{ij} x_i x_j = 1$.

If we use the known relationship for the electric induction vector in the form $D_i = \varepsilon_0 \varepsilon_{ij} E_j$ and solve a set of Maxwell equations, we find out that in a given direction, two electromagnetic waves with mutually orthogonal polarization can spread in the selected materials, having different rates of spread. The direction and polarization of waves can be found from the optical indicatrix. The directions of these two waves represented by the vectors $D^{(1)}$ and $D^{(2)}$ can be found as the intersection of the equatorial plane of the indicatrix with the plane perpendicular to the wave vector $k$, and both vectors have the direction of the major axes of the ellipse (indicatrix), which can be seen graphically in Figure 5.8.

![Figure 5.8 Optical indicatrix and optical double refraction](image)

From Figure 5.8 shows that the indices of refraction for the two waves are identical to the length of major half-axis of indicatrix, whose equation has the general form

$$\frac{x_1^2}{n_1^2} + \frac{x_2^2}{n_2^2} + \frac{x_3^2}{n_3^2} = 1,$$

where $n_i = \sqrt{\varepsilon_i}$. A more detailed analysis of the problem of symmetry of optical properties shows that crystals can be divided into three groups.

In *biaxial* crystals symmetry of a higher order than two is missing. This includes crystals of the triclinic, monoclinic and rhombic crystal system. The
three main axes of the ellipsoid are both axes of the second order. The triclinic crystal, orientation of the optical indicatrix is not related to the crystal symmetry. Ellipsoid has two circular equatorial sections symmetrical to the two main axes and containing the third axis. Normal for these sections is called the optical axis. If the waves spread in the direction of the optical axes, then there is only one index of refraction of a size equal to the radius of the corresponding circle. Therefore, when the light spreads along the optical axes, there is no double refraction and materials behave as isotropic.

For uniaxial crystals, we have symmetry axis \( A_n \), where \( n > 2 \). One of the principal axes of ellipsoid is its rotation axis. If the wave spreads in the direction of this axis, the wave front intersects the indicatrix in the shape of a circle, there is only one refractive index and polarization is arbitrary. Optical indicatrix of uniaxial crystal is determined by two indices of refraction \( n_0 \) and \( n_e \), where \( n_0 \) is the refractive index of the ordinary ray, and \( n_e \) is the refractive index of the extraordinary ray corresponding to the direction \( A_n \).

The equation of the indicatrix for the uniaxial crystal has the form
\[
\frac{x_1^2 + x_2^2}{n_0^2} + \frac{x_3^2}{n_e^2} = 1. \tag{5.10}
\]
If \( n_0 < n_e \) (for example for quartz), the crystal is called positively uniaxial, if inequality is reversed, i.e. \( n_0 > n_e \), then the crystal is called negative uniaxial. If two waves with mutually orthogonal polarization spread in the uniaxial crystal, the refractive index for one of them is independent of the direction of the wave spread and its value is always \( n_0 \), while for the other wave, the refractive index alters within the range from \( n_0 \) to \( n_e \).

For isotropic materials, having several axes of higher order than two, the optical indicatrix has several axes of rotation, that is, it degenerates to the spherical surface, therefore one value of the refractive index. In cubic crystals (4A3) or glass, and liquids, the light wave propagates at the same rate and polarization in any direction.

To solve practical problems from the area of electromagnetic wave propagation, it is useful to introduce the concept of the refractive index surface. As mentioned above, the radius - vector indicatrix is proportional to the refractive index of the wave. It will be appreciated that the refractive index is inversely
proportional to the wave propagation speed. The surface refractive index is a double surface, because two waves with mutually orthogonal polarization and speed can spread in every direction. It consists of a sphere and an ellipsoid (Figure 5.9) that touch at two points on the optical axis. The length of the second half-axis is equal to $n_e$ and the radius of the sphere is equal to $n_0$. The direction of energy transfer is perpendicular to the refractive index surface. For the ellipsoid, the direction of wave propagation can form a certain angle $\alpha$ with normal to the elliptical axis. This angle is zero for the spread of the wave in the direction of the major axes.

In conclusion, let us recall some important facts. From a quantitative point of view, differences between $n_0$ and $n_e$ are small and the optical indicatrix is very close to spherical surface (for the quartz crystal $n_0 = 1.54$ and $n_e = 1.55$). It is known that the dielectric permittivity is dependent on the frequency, and a different indicatrix corresponds to each frequency band.

### 5.3. Opto-elastic properties of solids

The deformation of the crystal under the application of mechanical stress can lead to the deformation of the optical indicatrix and thus changes in the conditions for electromagnetic wave propagation in such a deformed material. This phenomenon is used in technical practice in *photo elastic measurement* to diagnose a stress state in solids. In addition, in the piezoelectric materials, a
contribution to a change in the indicatrix occurs as a result of an electro-optical phenomena, which we will discuss later.

We will now deal with Pokkels description of the static deformation of an isotropic non-piezoelectric material (such as cubic crystals).

The optical impermeability tensor then can be expressed using the deformation tensor in the form

$$\Delta B_{ij} = p_{ijkl} S_{kl}.$$  \hfill (5.11)

$S_{kl}$ is the deformation tensor components and dimensionless components $p_{ijkl}$ form so-called \textit{photo elastic tensor}.

Similarly, we can also express the optical impermeability tensor using the stress tensor in the form

$$\Delta B_{ij} = \pi_{ijkl} T_{kl},$$  \hfill (5.12)

Where the tensor $\pi_{ijkl}$ is called \textit{piezo optical tensor}. If we use the relation for the generalized Hook’s law in the form

$$T_{kl} = c_{klmn} S_{mn},$$  \hfill (5.13)

we obtain the relation between the above-defined tensors in the form

$$p_{ijkl} = \pi_{ijkl} c_{klmn}.$$  \hfill (5.14)

\section*{5.4. Electro optical properties of solids}

Changes in optical indicatrix may be caused even by the electric field on the crystal. Such a phenomenon is called \textit{electro-optical effect}.

As in the previous case, we can express the impermeability tensor in the form

$$\Delta B_{ij} = r_{ijp} E_p,$$  \hfill (5.15)

where $E_p$ is the electric field strength.

Analogously to the piezoelectric tensor, the \textit{electro-optical tensor} $r_{ijp}$ is a tensor of the third order and it is zero for centrally symmetric crystals.

In piezoelectric materials, the spreading of elastic wave is accompanied by the formation of a longitudinal electric field. Due to the existence of the optoelectronic phenomenon, this electric field causes changes in the values of the
dielectric permittivity, so in addition to the previously described direct electro-optical phenomenon, indirect electro-optical phenomenon occurs in piezoelectric as well.

Note:
In addition to the natural double refraction, there is also artificial double refraction induced by external fields acting on the environment where the cleavage of the beam takes place. If the cause of the medium anisotropy is electric field, we talk about Kerr effect. For example, if nitrobenzene is placed in electric field, double refraction occurs. Anisotropy relaxation time is $10^{-9}$-$10^{-10}$ Hz. Kerr effect in this material is used for the rapid modulation of light.

Cotton-Mouton effect arises upon insertion of a suitable medium to the magnetic field, and it is analogous to Kerr effect. Its realization, however, needs very strong magnets with the value of the magnetic field strength of $H = 10^7$ Am$^{-1}$.

5.4. Ferroelectrics

Ferroelectric materials are relatively broad class of materials with very significant hi-tech applications. In ferroelectric state, the centre of gravity of the positive charges in the crystal does not correspond to the centre of gravity of the negative charges.

The ferroelectric crystal in the normal dielectric state does not usually exhibit substantial hysteresis if the electric field increases and reverses direction slowly.

In some crystals, the ferroelectric dipole moment cannot even be changed by an electrical field of the maximum usable strength, which still does not lead to electric breakdown of the crystal.

Ferroelectric state is usually lost above a certain temperature, known as the phase transition temperature. The crystal is then in the so-called paraelectric state.
Thermal movement tends towards abolition of the arrangement. Some crystals remain ferroelectric up to the thaw point, so they do not have the Curie point \( (T_c) \) (transition ferroelectric-paraelectric).

Ferroelectric crystals can be divided into two major groups.

1. **Class of ferroelectrics with transition order-disorder** comprises crystals with hydrogen bonds those shown in Figure 5.10.

![Figure 5.10. Ferroelectric crystals of the type order disorder](image)

<table>
<thead>
<tr>
<th>Type</th>
<th>Formula</th>
<th>( T_c, \text{K} )</th>
<th>( P_{max}, \text{esu cm}^{-2} )</th>
<th>( P_{max}, \text{pm} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>KHP</td>
<td>123</td>
<td>10000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KD</td>
<td>213</td>
<td>7500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RbHfPO₄</td>
<td>147</td>
<td>10000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RbHf₄O₁₂</td>
<td>111</td>
<td>10000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KH₃AsO₄</td>
<td>56</td>
<td>15000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CuFe</td>
<td>670</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2. **Class of displacement type ferroelectrics** comprises ionic crystals with the structure related to the structure of perovskite and ilmenite is shown in Figure 5.11.

![Figure 5.11. Displacement of the charges in crystals of Ba Ba Ti O₃](image)
In terms of the structure, a ferroelectric crystal generally consists of the domains, i.e. areas in which polarization has the same direction, while the direction of polarization in adjacent domains is different. When the volumes with oppositely oriented polarizations are equally large, the crystal as a whole behaves just as if it had not been polarized, which is shown by measuring the charge on the electrodes covering its ends. Real image of ferroelectric domains is shown in Figure 5.12.

![Figure 5.12 Real appearance of ferroelectric domains](image)

At so-called Curie point, ferroelectric substance passes into a para-electric state and Figure 5.13 shows the relationship for the Curie law together with its experimental verification.
Figure 5.13. The Curie law and its experimental verification

Legend: permitivita – permittivity, permitivita perovskitů v paraelektrickém stavu – perovskite permittivity in the para-electric state, jako funkce – as a function, podle práce – according to the work

5.5. Piezoelectric materials

The physical essence of this phenomenon consists in the fact that mechanical deformation of certain crystals results in a polarizing charge on their surface (direct piezoelectric effect), or vice versa, if suitably oriented plates made from such crystals are placed in a high frequency field, they begin to mechanically oscillate with its frequency. This phenomenon was discovered in 1880 by Pierre and Jacques Curie. In connection with the discovery of piezoelectricity, Pierre Curie formulated two principles.

The first principle says: The phenomenon has all symmetry elements having the reasons leading to this phenomenon.

The second principle says: The asymmetry of the effects must pre-exist in the causes.
The piezoelectric effect is schematically illustrated in Figure 5.14.

Figure 5.14. Description of the direct piezoelectric effect. a/ undeformed crystal, b/ polarization for deformation in the direction Y, c/ polarization in deformation in the direction X
Legend: piezoelektrické látky – piezoelectric materials

For the areal density of the polarizing charge of quartz, the following relation applies: \( \sigma = k \frac{F}{S} \), where \( F \) is the force, \( S \) is the area of the plate and \( k = 2,3 \times 10^{-12} \) C/N for quartz.

We know the direct piezoelectric effect, in which under the influence of mechanical deformation polarization of the crystal occurs, and it applies

\[
D_i = \varepsilon_{ij} E_j + e_{ijk} S_{jk}, -e_{ijk} = \left( \frac{\partial T_{jk}}{\partial E_i} \right) ,
\]

5.16
where \( \varepsilon \) are piezoelectric constants, \( S \) is deformation and \( T \) is the mechanical stress, \( \varepsilon \) is the dielectric tensor.

Indirect piezoelectric effect consists in the fact that if an electric field is brought to a piezoelectric crystal, the crystal is mechanically deformed and the following relation applies

\[
T_{jk} = c_{jkm}^E S_{lm} - e_{ijk} E_i - e_{ijk} = \left( \frac{\partial T_{jk}}{\partial E_i} \right). \tag{5.11}
\]

Because it applies that \( S_{jk} = S_{kj} \), piezoelectric tensor \( e_{ijk} \) is symmetrical according to the last two indices, and therefore it applies that \( e_{ijk} = e_{ikj} \). As a result of the said symmetry, the total number of components of the tensor of the third order, such as the piezoelectric tensor, reduces to 27.

The best known piezoelectric materials are:

- SiO2
- LiNbO3
- GaAs
- ZnO
- CdS
- Se
- piezoceramic
- PVDF electrets

5.6. Liquid crystals

At the end of the last century (in 1888), synthetic liquid crystals were prepared for the first time (Liquid Crystal, LC). The scientists who stood at the cradle of this development included Reinitzer, Lehmann, Ostwald, and others. In the early stages of the research, the surprising properties of liquid crystals were connected with living nature.

A mesomorphic state is intermediate between a solid and a liquid state, and it is sometimes considered as the fourth state of matter. It is characterized by a high degree of orderliness (order) of molecules at a large distance.
In a certain temperature interval, the mesomorphic compounds may have more stages of transition of the same type, or they may go through different types of transitions. Such substances are called **mezzo-polymorphic**

It was found that by heating clear crystals of some compounds at the thaw point $T_1$, we obtain an opaque viscous liquid or a consistency which has exceptional properties. The properties are maintained up to the temperature $T_2$. *Once it has been exceeded, the substance becomes completely liquid and isotropic.* In the temperature range, the light in a material does not spread equally in all directions, i.e. the substance does not have the same absorption coefficient and the same refractive index (optical anisotropy).

Today, the concept liquid crystal includes exclusively the compounds which under precisely defined physical conditions have some properties of liquids and others pertaining to conventional crystal.

Substances passing into the mesophase under the influence of temperature are called **thermotropic.** The same effect is achieved by dissolving initially crystalline substance in a suitable solvent. Substances of this kind are called **lyotropic.**

In the year 1968, other physical facts were discovered: sensitivity to temperature, pressure, electric and magnetic field, radiation, which allows to transform the most diverse physical quantities on the light signals. *The components allow to achieve colour change, translucency (transparency) mutation or storage properties with extremely low heat activating input.*

*Given the chemical composition, these are organic compounds.*

Liquid crystals are mostly **aromatic and rarely aliphatic compounds and exceptionally other substances.** Aromatic compounds are derived from benzene hydrocarbon nucleus, aliphatic from noncyclic cores, in particular methane.

It has been stated that the compounds characterized by **dimer** or polymer **linearity** containing in its constitution dipolar groups and polarizable bonds are capable of forming mesomorphic states. In the aliphatic acid, the occurrence of two double bonds in the molecule is a necessary condition.
Legend: the central (middle) group X and the end groups Y, Y’ determine whether or not the compound will be mesomorphic.

If the groups X, Y, Y’ are dipolar, with a strong dipole moment, or polarizable, they will show attraction towards mesomorphism. Side groups, lowering the degree of the chain linearity paralyze the ability of forming mesophases. The central (bridging) group X may be symmetrical or unsymmetrical.

Aliphatic compounds with extremely long molecular chain rarely form liquid crystals. Compounds characterized by the permanent dipole moment, i.e. linear and polarizable molecules, are suitable for the formation of liquid crystals.

In chemical point of view, these requirements are met by the compounds with a large number of unsaturated bonds. They are especially aromatic nuclei to which other groups with multiple bonds are attached.

First, we will describe smectic liquid crystals. This kind of SLC is characterized by oblong linear molecules deposited in parallel layers (layered texture). Longer molecules axes have stable orientation relative to the surface of the crystal. Most often they are perpendicular to the surface.

Newer research has discovered orientations in which the axis of molecules form a certain angle to the surface dependent on the temperature. The layer thickness is approximately equal to the length of the molecule. Inside the layer, there is not a distant molecular arrangement.

**Orientation of the axes in parallel layers is stable.** The crystal appears as a solid. There are other textures, about which we know little at present, but they are extensively studied by modern physical methods.
It was found that the orientations of molecules in the individual layers do not have to be identical. The difference may occur also with respect to molecular arrangement in the same layer. Specifically, the directions of dipoles are identically or non-identically parallel. Possible types of smectic crystal structures are shown in Figure 5.15.

![Smectic types of structures](image)

Figure 5.15. Smectic types of structures

Smectics are closest to solid substances due to the high viscosity - internal friction and a laminate-like texture. At the melting point, the lateral bonds between the individual layers are released; these bonds, due to low mutual adhesion, can slide over each other without detriment to order. The transition liquid crystal – isotropic liquid is characterized by disturbing the order in the layer due to the thermal process. The basic requirement of a smectic compound is mutual parallelism of molecules in the layer - order.

Another type of liquid crystals are nematic liquid crystals. Nematic liquid crystal - NLC molecules are not arranged in specific layers, but the centres of gravity of the molecules are stochastically distributed as in a normal liquid. The centres of gravity are not stationary, but move chaotically. Molecules are elongated, rod-shapes and mutually parallel to long axes.
They retain parallelism despite its movement, characterized by 4 degrees of freedom. The molecules perform translation in the axial direction and rotate about the long axis (Figure 5.16).

Figure 5.16. Nematic types of structures

Newer exploration in nemantics have shown that in addition to the classical configuration, there are other pseudo-layer textures which represent a transition between the conventional nematic texture and layered smectic texture. X-ray analysis has shown that they form domains. The single domains have different molecular axis orientation. The domains themselves show a hint of layering.

The basic postulate for nematic character is collineation of odd and even molecules. The last group of liquid crystals are cholesteric liquid crystals. CLC crystals got their name from cholesterol, from which they were originally harvested. Elongated molecules are arranged in parallel layers about 200 nm apart, i.e. approximately hundredfold compared to smectics. Each layer contains molecules with long axes in the layer plane having a coinciding orientation, which is, however, different in the individual layers.

In two adjacent layers, the axes of the molecules are slightly turned to each other by a constant angle $\Delta \varphi$. This angle is different for various materials. After 1000 layers, the molecule axes are already antiparallel. This requires the total thickness of the liquid crystal layer of $200.10^{-9}$m (Figure 5.17).
Along an axis perpendicular to the plane of the layers, molecules form a helical surface below them – a cholesteric helix with period L. Periodic texture including defects can be observed in a polarizing microscope.

Figure 5.17. Cholesteric liquid crystal

Some liquid crystals in a mesomorphic state change colour due to the effect of temperature (thermal coloration).

Mixtures were prepared with mesomorphic interval only 0.01 °C wide. This means that if the temperature goes through this interval, coloration will cover the whole colour spectrum. The blue hue corresponds to the highest, the red one to the lowest temperature.

_Nematic liquid crystals with positive dielectric anisotropy_ (dipole moment has the direction of the longer axis of the molecule), to which pleochroic dye was added, _colour under the effect of an electric field_.

If the dye molecule is parallel to the electrical component of the electromagnetic wave by its long axis, the light is absorbed by the dye, and the observer can only see its complementary colour.

Liquid crystals are nowadays mainly used for the construction of display units of computers, televisions and the like.

A display cell comprising two parallel glass slides, which have conductive electrodes of SnO₂ on the inner walls. Between the electrodes, there is a layer of liquid crystal 35 to 100 microns thick. The desired spacing of the electrodes and hermitisation are realized by a spacer 4 of mica, nylar, Teflon, PVC. In the production, demanding requirements are placed on nearly absolute plane parallelism of the electrodes and high LC material homogeneity (Figure 5.18).
A display cell is a passive element, it does not generate light. For the visualization of information, an auxiliary light source is needed. Visualization is caused by modulation of the light flux by excitation voltage. In the mode of transmitted TM light, both electrodes must be translucent to enable the light to pass through the system from the side of the source to the observer side. The source is hidden from the observer. The observer can see light scattered by the cell, which appears bright on a dark background. The beam of light rays passes through the LC layer once (Figure 5.19).

In the mode of the reflected RM light, the rear electrode is opaque and acts as a mirror. The largest reflected contrast is achieved by vapour deposition of Ni, Ag, Au, Ta, Cr, reflected on a glass plate. The light source and the observer are on the same side with respect to the LC. The imaging ray passes the LC medium twice. A reflex cell can operate only with the use of incident light from the environment. Each of these modes may be direct or indirect.

In the direct mode, the released or reflected light flux is greater in non-excited LC state, i.e., without connected external voltage.
Indirect mode is characterized in that the light flux is absorbed without external voltage. If excitation voltage is connected, the ratios reverse. In the dynamic scattering mode, TM is direct and RM indirect mode.

In TM, the imaging cell becomes visible without connected voltage and it goes out by connecting electrical voltage. In RM, electric voltage makes the cell visible. If the voltage is removed or drops to zero, the incident light from the source passes through the cell, it is not reflected, and hence RM is only very slightly visible.

Figure 5.19. Imaging modes of LC cell
Legend: kolmica dopadu – incidence perpendicular
Summary of concepts of the chapters (subchapter)

Types of dielectrics polarization, phenomenological description of polarization, micro-structural description of the polarization, optical properties of materials, ferroelectrics, piezoelectrics, liquid crystals.

Questions on the explained topic

1. Describe the individual types of polarization.
2. What macroscopic variables describe the polarization phenomena?
3. What is the definition of the polarization vector?
4. Write and explain Clausius-Mosotti equation?
5. What qualities do monoaxial and biaxial crystals have?
6. What is optical indicatrix?
7. Classify types of ferroelectrics.
8. Explain a piezoelectric phenomenon.
9. Explain the pyroelectric effect
10. Explain the optoelastic and the photoelectric effect.
11. Describe the individual types of liquid crystals.
12. Describe imaging and coloration of liquid crystals.