Liquid Crystals In Education – The Basics

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Abstract
The introduction of teaching about liquid crystals is discussed from several points of view: the rationale why to teach them, the basics about liquid crystals or what the teacher should teach about them, the fundamental pre-knowledge of students required, the set of experiments accompanying the teaching and the brief report on the already performed testing of the teaching module.
Keywords: Liquid crystals, physics education, classroom physics.

Introduction

Physics teachers often complain about extensiveness of physics syllabus and curricula, about shortage of time and about the lack of student's interest. The idea of introducing new, modern and consequently often more demanding topics seems therefore completely obsolete. However, in this contribution I argue that this is not the case and that introduction of a new topic into the school program is beneficiary for students, their knowledge and their appreciation of science in general. Why do I believe it? Usual physics curricula are bound to topics, which are more than hundred, often also more than several hundred years old, if one considers their discovery and/or comprehension. Topics are often considered idealized, detached from everyday experiences and from everyday life. Teachers are usually aware of difficulties, which application of "pure" school physics to everyday problems brings to discussion – several intertwined phenomena have to be considered, approximations are necessary and the explanation is often accessible to most talented students only. Therefore explanations of everyday phenomena, new technologies and especially new results of academic research are almost never met in the classroom. The idea about physics students get is the physics is old or even dead, boring and not relevant for anything. If the teaching is accompanied by a lot of calculation that students perform following certain patterns and strictly guided laboratory work, students' curiosity is not stimulated (Osborne, 2003).

It might be useful to find few topics, which are relevant for everyday life, where the scientific community has not solved all the problems yet and that the basic explanation of the topic can be built on the knowledge accessed through usual physics curricula. Let me quote few of them: superconductivity and flying frogs (Bonnano et. al. 2011), semiconductors and modern electronic (Garcia-Carmona 2009), liquid crystals and portable screens (Pavlin, 2011a).

In the continuation we will focus on the last of the three quoted above, on *liquid crystals*. We use applications, which are based on peculiar properties of liquid crystals, everyday – an important part of communication takes place through screens of mobile phones and laptops, which are based on liquid crystals. Scientific community, which is engaged in research of liquid crystal, counts several thousands of people. The prominent scientific journal Physical Review E has a special part devoted to them. The liquid crystals are certainly not the topic, which is scientifically dead or almost forgotten and which is not related to anything modern and useful (Takezoe, 2010).

A fundamental understanding of liquid crystals can start from the knowledge obtained within general physics curricula: the states of matter, the refraction of light and polarization states of light. Finally, liquid crystals are relatively easily accessible and allow for several hands-on experiments, which allow students to construct the new knowledge through constructing personal understanding by active learning.

The paper is structured as follows. In Section II a short overview on liquid crystals, the properties of molecules, which form them, the properties, which enable the applications and their observations and measurements, are presented. In Sec.III the necessary physics comprehended by students before discussing liquid crystals and the goals the teacher pursue by teaching of liquid crystals is discussed. In Sec. IV the set of experiments used in teaching liquid crystals is described in more details. In Conclusions we reflect on our experiences on teaching liquid crystals and we discus some open and future problems.

Liquid crystals – a delicate state of matter

Liquid crystals are organic materials, which have an additional state of matter between the liquid state and the solid state (Collings, 1997). This state of matter is called liquid crystalline phase, because the material in this phase flows like liquids and possesses orientational or often also translational order, which is reflected in anisotropic properties, which is typical for crystals. There exists a whole zoo of various liquid crystalline phases with a large variety of properties. Sometimes many of them are found in a single material. The name *liquid crystals* is reserved for materials, which posses at least one of the liquid crystalline phases.

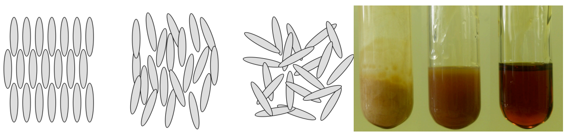

Figure 1. *Three states of a liquid crystal. Above and correspondingly below from left to right: the crystalline phase, the nematic phase, the isotropic liquid phase.*

Liquid crystals are usually formed by molecules, which are elongated. The crystalline state becomes stable when van der Waals attractive forces prevail over entropic motion of molecules. The opposite is true for the liquid phase. The entropy and with it connected molecular motion prevails over energetically favored fixed positions in the crystalline lattice. Liquid crystalline molecules are typically 3 nm long and have diameter of about 0.5 nm. As attractive van der Waals forces decrease with the high order of distance, intermolecular interactions become very sensible to the mutual orientations of molecules. Two elongated molecules attract more when their long axes are parallel as they attract when they are perpendicular. Therefore in the temperature range below the liquid phase and above the solid state the structure, the phase becomes stable, in which the motion of molecules is still possible, but molecules cannot be randomly oriented and favor parallelism in long molecular axis.

Our concern will be the simplest liquid crystalline phase known: the *nematic phase*, which is used in screens. The simple cartoon presents the difference between the liquid state, the liquid crystalline state and the crystalline state (Figure 1). The molecules are schematically presented as ellipsoids due to their assumed fast rotation and the elongated shape. In the crystalline state (Figure 1 – left) they are ordered orientationally and positionally. In the liquid state (Figure 1 – right) molecules are orientationally and positionally disordered. In the nematic liquid crystalline phase (Figure 1 – middle) only orientational order is established upon cooling but molecules are still free to move within the sample volume.

The liquid crystalline phase possesses therefore properties of both: the liquid, as molecules do not have well defined positions and the solid, as there exists a certain order and the anisotropy due to it. The material in the liquid crystalline phase has anisotropic properties, which can be clearly concluded from the structure. The two properties are the most important for application – optical anisotropy and the birefringence of the material due to the structure of the phase and the easy manipulation of molecular orientation and the phase structure by external electric field due to the liquid like properties of the phase. In the usual bulk sample, the molecules are ordered only locally. Molecules in volumes of around 10^6 μm are oriented in the same direction. In different parts of the sample, this orientation differs. The light scatters on interfaces between differently oriented areas, which is the reason for a milky appearance of the phase (Fig. 1 – middle).

The image in the laptop screen (Fig.2) is formed of pixels. Each pixel has three colors and the brightness of each is controlled by electronics. The three pixels together form an optical unit. Fig. 2 – presents the image on the laptop screen and magnified parts of different parts.

Figure 2. *The screen with the colorful background and rectangles of single color squares, two colors mixture squares and the white square. Marked signs are enlarged. Three fundamental colors form one pixel.*

The basic structure of the screen is the following. The liquid crystal in the nematic phase is found between the two glass plates. The large glass plates are prepared in the clean room in the absence of any dust and they are rubbed with the velvet cloth in a certain direction. Glass surface has scratches in the rubbing direction. Elongated molecules stick to glass with their long axes along the scratches and the molecules orient with their long molecular axes in the direction of scratches. The orientation of scratches on the two glass plates making the screen is perpendicular one to another. The liquid crystal is filled between the two glass plates. The structure of the liquid crystals adjusts to the enforced orientation by making the helix (Fig 3. -left). The fundamental part of the screen (the pixel structure) is also the two polarizers, one of them on each external side of the two glasses. Transmission directions of polarizers are oriented along the scratches on the glass plates and consequently parallel to the orientation of elongated molecules close to the surface. The transmission directions of both polarizers are therefore perpendicular. The pixel has three optical units, each unit is controlled by the electronics, which establishes the electric field between the plates and changes the structure of the liquid crystal between the plates. When the electric field is applied, molecules of the liquid crystal polarize and tend to orient with their long axes along the electric field. The level of reorientation depends on the magnitude of the electric field (Fig. 3 –middle, right). To provide colors, the color filter is added. So, one pixel has three separately guided electronics for each optical element, the one for each fundamental color.

How does the optical unit work? There is a source of light at the backside of the screen. The light falls on the polarizer and becomes polarized. If there is no electric field, the structure of the liquid crystals is like it is seen in Fig. 3 –left. During the propagation of polarized light through the liquid crystal its polarization state changes. The changes are simple, the polarization direction rotates, it follows the direction of the long molecular axis and rotates for 90° from one glass plate to another. As the transmission direction of the polarizer is perpendicular to the one on the opposite plate, the light is simply transmitted through it and the optical element is bright. That part of the pixel shines its color fully. When the electric field applied is large, molecules orient along the field and the state of the polarization does not change during the propagation (Fig. 3 – middle). The second polarizer absorbs it and the optical element is dark. These were two extreme situations known as the dark and the bright state. Application of smaller voltages and consequent smaller electric fields does not lead to full reorientation of molecules and the structure does influences the polarization state of the transmitted light more or less, depending on the voltage. The light is more or less absorbed by the second polarizer and the grey scale is achieved. In combination with the color filter the grey states result in more or less bright colors (Fig.3 right).

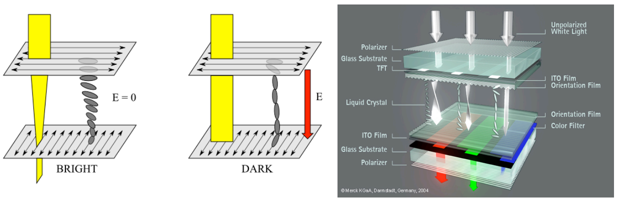

Figure 3. *The bright (left) and the dark state (middle) and the pixel in a general state: bright red, grey green and dark blue (right).*

The basics one should know before or could be taught by liquid crystals

If one wants to place the liquid crystals in the school, one could consider various options. Teaching about liquid crystals can be an example of how the existing knowledge of students is used in applications. On the other hand, the teacher can start with liquid crystals at the beginning of thermodynamics as a motivation that stimulates students also for electromagnetism and optics. One can also use liquid crystals for the introduction of some concepts like a double refraction and polarization of light.

Let us now discuss concepts and phenomena that should be known before discussing liquid crystals or could be introduced by teaching about them.

- *Phase transitions:* There are several states of matter; three of them are most common – solid, liquid and gaseous state. The phase transition between the two states occurs at a certain temperature. The transitions we usually have experiences with are of the discontinuous type and are associated with the latent heat.
- *Anisotropy:* Is a general term for the phenomena, where measurements of a certain property depend on the direction. Few examples:
    - The wood could be cut straight when the sawing directions is perpendicular to wood fibers but the saw easily changes the direction when the sawing along the fibers takes place
    - The knitted cloth extends or shrinks in the direction of knitting usually different that perpendicular to it
    - Walking along the lines of vines in a vineyard is easier than perpendicular to them

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   - Polarizer absorbs one direction of polarization differently than the one perpendicular to that direction.
- *Molecular polarizability:* When molecules are found in the electric field, the internal structure of the molecule changes. The electron cloud is attracted toward the positive source of the electric field and consequently the center of the negative and the positive charges do not coincide. As a result, a dipole is induced, a torque appears and the molecule tends to orient with the induced dipole along the electric field.
- *Polarization of light:* The light is an electromagnetic wave. When the time and spatial dependence of the magnitude and the direction of the electric (magnetic) field in the electromagnetic wave is known, the light is polarized. Three typical types of polarizations are usually discussed – linear, circular and elliptic. If the light is linearly polarized, the electromagnetic field has only one direction and changes the magnitude. For the circularly polarized light, the magnitude of the electric field is constant, but the direction changes in a circular manner. The elliptically polarized light is the combination of both. The name comes from the shape, which is described by the electric field vector.
- *Polarizers:* Polarizers are anisotropic materials, which absorb the light polarized in one direction, called the *transmission direction*, more than the light polarized in the direction perpendicular to this direction. For a general polarization of light, the intensity of transmitted light is proportional to the square of the electric field component along the transmission direction.
- *Color filters:* The absorption of the light in colored transparencies depends on the wavelength of light. The spectrum of transmitted light is different from the incident light due to the different absorption of color components of light and the incident white light becomes colored.
- *A double refraction and a birefringence:* When light propagates through an optically anisotropic material, it splits in two beams, which have mutually perpendicularly polarizations and different speeds of propagation. Due to the different speeds of lights, the material has different refractive indexes for the two polarizations and they refract differently. As one single incident light beam refracts in two beams, the phenomenon is called the *double refraction*. The difference between the two refraction indexes is called the *birefringence*.
- *The order parameter:* The order parameter is a measure of the order in the liquid crystalline state. Different liquid crystalline phases are described by the state of order by one or even more order parameters each giving different information about the type of order. The only order parameter that is important in the nematic phase is the orientational order parameter, which measures the level of orientational order in the sample.

As mentioned before, almost all concepts can also be introduced through experiments with liquid crystals. The teacher may choose her or his own approach; she may use liquid crystals from time to time as a motivation or present them just as something interesting in addition to curricular topics.

The teaching module on liquid crystals

One starts with consideration, what about liquid crystals is so important, that a general public would deserve or would be interested to know. There is no known theory about introduction of new modern topic into education up to my best knowledge. Therefore, what I intend to suggest here is therefore a personal opinion only.

The basic goal is to explain the function of the liquid crystalline screen, not all the details but the principle of the image formation on the screen i.e. how the color of the pixel appears.

The magnified screen is presented in Figure 3, where also pixels can be seen. The main goal of the teaching module is the understanding of the pixel functioning.

What one needs to know for this? If one leaves the details of the screen illuminations, the basic constituent is the "cell" consisting of two polarizers, two glass plates, the oriented liquid crystal between the two plates and the electronics, which control each part of the pixel. The electronics influences the liquid crystal and consequently changes the polarization state of transmitted light. There are few points which students should become familiar:

- Liquid crystals have a special phase of matter with very special properties.
- Properties of polarizers.
- Birefringence and the consequent double refraction is a special property of optically anisotropic materials.
- Birefringent material changes the polarization state of the transmitted light.
- The structure of the liquid crystals in the nematic phase is anisotropic.
- It is very sensitive to external stimuli like electric or stress fields.

All of the quoted above is introduced by means of hands-on experiments, accompanied by active learning.

A special state of matter

A small volume of a liquid crystal (for example MBBA or 5CB) is placed in a small glass tube and is sealed. The tube is placed in the ice until the content freezes. The three states of matter – the crystal, the liquid crystal and the liquid could be either observed only or a more rigorous measurement of the transition temperatures can be performed.

If former, the student places the liquid crystal in the glassy container into the water at room the temperature until the content melts. Than it is placed in the hot water, around 50°C satisfies, and the student waits until the content becomes clear. Students describe their observations.

For more detailed measurement, the students gradually heat the container within the water bath and measure the temperature of the bath, when the crystal begins to melt and when the milky liquid becomes clear. A discussion after the experiment has to emphasize, that the milky appearance of the material was present from around 20°C to around 40°C. Although the milky appearance of the liquid crystal is similar to the mixture of crushed ice and water, the two examples are not the same. A mixture of crushed ice and water exist solely at 0°C and it presents the coexistence of phases at the melting temperature. The similar appearance of the liquid crystal is present in temperature range of 20°C, which indicates an existence of a new special phase with different properties.

Anisotropy

The most important property of the liquid crystalline phases is the anisotropy. The anisotropy is a common name for properties, which depend on directions of the external stimuli. Nice examples are knitted cloths. Everybody knows that a knitted pullover or a cotton T-shirt extends in one direction can also imagine the speed of moving through the vineyard (Fig.4). If the runner is running along the lines of vines, she or he can move freely. But if the direction of running requires passing the vines, the runner has to slow down for a while and then speed up again. The impact of vines on the speed is the most tremendous, when the running direction is perpendicular to the lines of vines.

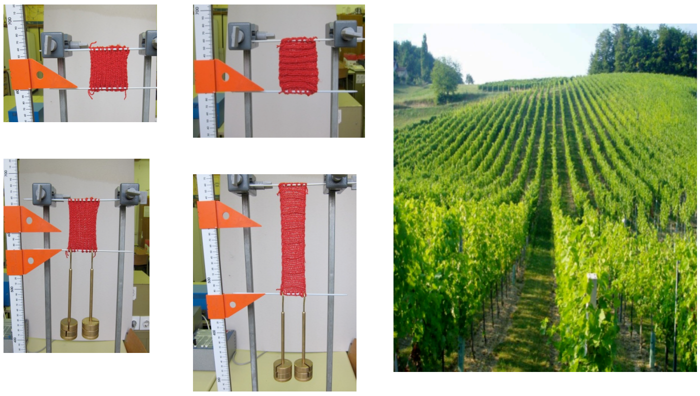

Figure 4*. Knitted pattern extends in one direction less than in the other (left and middle). The speed of running through the vineyard depends on the direction. Passing many lines of vine slows down the speed.*

The structure of the liquid crystal, especially in the nematic phase, where elongated molecules are oriented in one direction, implies the anisotropy in several properties like viscosity, absorption and the most important for applications - the anisotropy in optical properties – the existence of two different velocities of light for two different polarizations.

Polarizers and polarization states of light

If students are not familiar with polarizers, it is worth to make few experiments to introduce their properties and their use. Modern polarizers are made of polymers and are *linearly dichroic*. It means that they absorb light polarized in one direction more than the light polarized in the direction perpendicular to that direction. Larger absorption usually coincides to the direction of elongation of long polymeric molecules, which arises through the process of flattening and stretching the polymeric material. If the material is thick enough, the ratio between the intensity of the less and more absorbed polarized light becomes around 10:1 or even up to 100:1 for professional polarizers. The light after passing the polarizer is polarized and the direction of polarization is known by the orientation of the *transmission direction* of the polarizer, which is a known property of a polarizer. The light is linearly polarized because the usual polarizer is linearly dichroic. There exist also materials, which absorb opposite handedness of circularly polarized light differently and transmitted light is circularly polarized. They are often used for 3D projections and as filters in photo cameras. We will not consider them further.

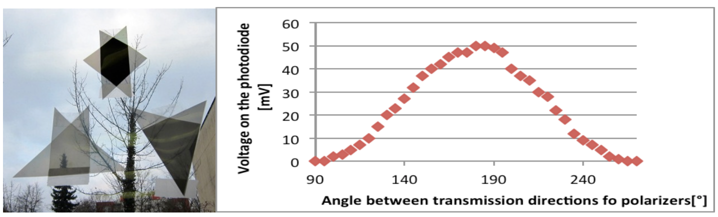

Figure 5*. Left: Three types of orientations for the two polarizers: parallel transmission orientations (left below), perpendicular transmission orientations (top) and general orientation (right below).*

Right: Intensity of transmitted light measured by the voltage on the photodiode in dependence on the angle between the transmission directions of the two polarizers.

If the second polarizer is placed in the beam of polarized light, the transmitted intensity of light depends on the orientation of the transmission direction of the polarizer. For the parallel orientations of the two polarizers, the intensity of the transmitted light is the largest, while the light is almost completely absorbed for the perpendicular orientations of polarizers (Fig 5-left) The intensity of light dependence on the angle between the orientations of the transmission direction of the two polarizers measured by a photodiode is presented in Fig.5 – right. The polarizer can therefore be used for determination of the polarization state of the light – how much is the light linearly polarized. In this function the polarizer is often called the *analyzer*. For an ideal linear polarization of light, one orientation can be found, for which the light is completely absorbed. The direction of the light polarization is perpendicular to it. If the light is a mixture of polarized and non-polarized light, the one orientation of the transmission direction transmits less than the one perpendicular to it. Similar is true for different states of elliptically polarized light. For example, single linear polarizer cannot distinguish between the ideal circularly polarized light and the non-polarized light. To distinguish these two states, the circular polarizer is needed. Also these experiments are beyond our interest in the very interesting physics of polarized light.

Effects of optical anisotropy – double refraction

Two mutually perpendicular polarizations of light have two different refraction coefficients. The light, which has a component of the electric field (the polarization) along the orientation of long molecular axis, polarizes molecules more than the light, which is polarized along the short molecules short axis. As a consequence, the refraction index for the former is larger and for the later is smaller. The beam of light, when it is incident under an angle on the ordered liquid crystal, refracts into two beams (Fig. 6), which are perpendicularly polarized.

The spatial separation of the two beams can be obtained by using the prismatic effect. The cell, which contains the ordered liquid crystal, should have a wedge shape. The cell is made as follows. A clean velvet cloth in direction rubs a clean, possibly new object glass, which is usually used for microscopy parallel to the short side of the glass. One side of the object glass is wrapped by several layers of food foil. A clean cover glass is also rubbed by velvet in the same direction as the object glass. A small drop of a liquid crystal is put on the object glass and is covered by the cover glass. Rubbing directions should be the same. The wedge cell is now heated by a hairdryer as long as the liquid crystal enters to the isotropic phase and becomes transparent. The cell is left to cool down and molecules orient along the scratches on the glass plates. As a result a prism formed of an oriented liquid crystal is formed. The experiment can start.

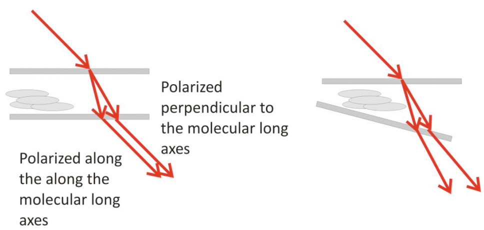

***Figure 6**. Left: Oblique incident light splits into two perpendicularly polarized light beams. As the cell is thin and the laser beam is relatively broad, they are still seen as one beam after passing the cell.*

Right: Prismatic effect changes directions of transmitted light and the two beams separate also spatially.

First students should predict the outcome of the experiment starting from the fact, that the material is anisotropic and has two refractive indexes. Students then shine the laser beam on the wedge cell and the beam splits to two beams seen as two bright spots on a distant screen. What are the properties of both light beams with respect to polarization if one remembers the procedure, the rubbing direction of the glasses? The polarization of the two beams is verified by the polarizer.

Properties of the perpendicularly incident polarized light on the anisotropic material

Double refraction manifests in splitting the incident light into two beams with mutually perpendicular polarizations. Another question is interesting: How the two different speeds of light affect the polarization state of light for the perpendicularly incident light? In this case the beam does not spatially split but the phase velocity i.e. the wave vector $\vec{k}$ has the same direction after passing the surface of the anisotropic material. The light still splits in two partial beams having the same direction of the wave vector but different velocities. Because wave vectors now differ, also the wavelength for both polarizations is different and both partial beams are phase shifted after leaving the sample. Because the phase shift depends only on the difference of the two refraction indexes, but not on their magnitudes, this difference has a name: the *birefringence*.

What does this actually mean? If the incident light is linearly polarized in general direction with respect to the rubbing direction i.e. to the orientation of the long molecular axes, the transmitted light is elliptically polarized in general. This means, that the second polarizer oriented perpendicular to the first polarizer, which polarizes light, now transmits the elliptically polarized light. The state of polarization depends on the phase difference, which depends on the wavelength of the light. If the incident light is white and contains all visible wavelengths, it could happen that the red and the blue part of the spectrum are almost linearly polarized in the same directions as the polarizer but green part of the spectrum is polarized almost perpendicular to it. The intensity of transmitted light depends on the state of elliptical polarization as seen in Figure 7 and as a consequence the transmitted light is colored. Rotating the second polarizer for 90° one obtains the complementary spectrum.

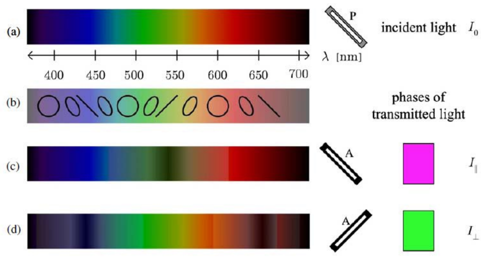

Figure 7. *(a) The spectrum of the incident light illustrated by a rainbow and the corresponding wavelengths. Direction of the incident polarization is marked by a polarizer. (b) The states of polarization after transmission. (c) The spectrum of the transmitted light for the second polarizer parallel to the incident polarization direction. The green part is mostly absorbed and the color of the light is magenta. (d) The spectrum of the transmitted light for the perpendicular polarizers. The red and the blue are absorbed more and the color is seen is green (Babič 2009).*

Experiments to show this are simple. Students take two polarizers, place them one above another and find the orientation of both, for which the intensity of the transmitted light is minimal. They insert between the two polarizers a simple glass plate, an object glass for example, and they rotate first the glass and then one of the polarizers. They observe that the inserted glass does not change the properties of the transmitted light. The whole structure behaves the same with and without the glass. Than students take a simple transparent sticky tape and glue two or three layers of it to the glass plate. The tapes should be a little shifted that effects of the tape having different thicknesses can be observed at the same time. Students predict what they will see, when a modified glass plate is put between the two polarizers. They repeat the previous experiment. Here the discussion, why colors appear may start or the explanation from before can be used.

The next step is: instead of the tape or another type of the foil like transparency a drop of a liquid crystal is put between the galls plates. The sandwich of two glasses and the liquid crystal becomes transparent and sometimes also colors are seen. More details can be seen under the microscope. The teacher should tell the student, that colors of the liquid crystals are one of the consequences of the birefringence but the colors of the pixel have a different origin.

How the pixel is manipulated?

Now, students are prepared to understand how the pixel is working. For the manipulation of the pixel, the structure of the screen has to be considered quickly. The screen consists of several parts that provide homogeneous illumination of the backside of the screen (Fig.1). The most important part of the screen is a sandwich of two glass plates rubbed in mutually perpendicular directions and filled with the liquid crystal, usually a mixture of several different liquid crystals, which has a nematic phase extending from very low temperatures below 0°C to rather high temperatures above 60° or 70°C. Obviously, the screen has to function outside in the cold winter and should not fail if it was left in a hot car during the summer. Both glasses are covered by polarizers with transmission direction parallel to the rubbing direction, Fig. 3, as explained before. The part of the screen that is seen from outside is covered by a color filter – each optical unit has three different very small color filters: red, green and blue. Finally, the lithography of electronics is made on both glasses and can guide each pixel separately. The electronics provides the electric field between the two glass plates.

Due to the rubbing, the long molecular axes of molecules orient in a helix as seen in Fig. 3. If the light polarized along the ordered long molecular axes enters this structure, the polarization of light follows the orientation and rotates for 90° from one side to another. As also transmission directions of both polarizers form an angle of 90° degrees, the light is transmitted and the situation presents the bright state of the pixel. If the electric field is applied, elongated molecules polarize along their long axis and the forces on a separated charge induce torque, which rotates molecules with their long axes toward the direction of electric field. The structure of the liquid crystal between the glass plates is changed and the rotation of the light polarization is no more complete. Instead, the light becomes elliptically polarized and for the extreme example, when all molecules are with their long axes perpendicular to the glass surfaces, the polarization of light is not affected during the transmission at all. In the last case, the light is absorbed in the second polarizer and the situation corresponds to the dark state of pixel. States in between are usually called grey states, which signifies that the light is absorbed only partially. The colors are therefore formed by the three primary colors of three pixels in the optical unit. Controlled is the grey level for each color. Examples of magnified screen for the primary colors, for the colors in the simple subtractive circle used by painters and for a white color are seen in Fig 3.

Unfortunately, construction of the pixels requires glass plates covered with a conductive layer, which is not easily accessible. Few experiments can be done with old screens of bad mobile phones. One dismantles a screen and applies the voltage from the simple battery directly to the contacts. The screen usually switches from bright to dark state and students can play by searching different combinations of contacts.

Conclusions

This extended abstract provides the basics of liquid crystals one needs when considers discussing liquid crystals with students. Described are basic concepts that can be introduced by liquid crystals or additionally illustrated by them. Basic experiments that help students to build the conceptual knowledge about liquid crystals are shortly presented and accompanied by additional explanations.

Before introducing the topic into the classroom our group assessed the existing knowledge about liquid crystals in the generation, which has just finished the high school. As expected, the concepts related to liquid crystals are almost unknown, most of them have heard the expression ”liquid crystals” in connection with screens, but that is all. Because of their use in screens, they usually quote that optical properties of liquid crystals are important, but not which of them (Pavlin 2011b).

We tested the teaching module, which consists of one hour and a half of a lecture and the two laboratories of the same duration – one hour and a half. The first laboratory is within the chemistry and they synthesize the liquid crystal MBBA. Students later use for experiments their own product. We tested the teaching module in two groups – the future physics teachers and the future primary school teacher. Both groups were in the first year of their study. The motivation and the interest was certainly higher in the group of future physics teachers. However, also future primary school teachers, where majority of students dislike everything related to science, were active during the laboratories and have shown a relatively high level of enthusiasm. The evaluation of knowledge has shown two traditional things. In the part of the test, which could be learned by heart – like a definition that liquid crystals were birefringent – the success was high – around 90%. Around 60% to 70% of students remembered well the activities from the lab work, what they have observed and how it was related to the properties of liquid crystals. This part hints – the preliminary data support this result – that students with lower achievements in the practical work have also lower results in reports on the practical work. Finally, the application of the new knowledge in new situations was rather weak, but the situation is rather similar in other fields of physics as well for the future primary school teachers. To their defense one has to add, that the physics course designed especially for them is very short, consisting of only 30 lectures in duration of 45 minutes and 10 laboratories in duration of an hour and a half. Unfortunately, the course for physicists cannot be directly compared to the course for the primary school teachers, because liquid crystals were a part of a subject, which is considered as a subject that presents students few interesting topics for their later more thorough study (Pavlin 2012).

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