Lap-tops, mobiles, iPods and liquid crystals

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ABSTRACT: A number of modern devices are based on liquid crystals. Liquid crystals themselves are still a vivid research topic, i.e. the scientific research community is still searching for answers to academic questions like understanding the origins of interactions that lead to complex structures, and the development of various applications based on their interesting but complex properties. In this contribution, the authors provide a short overview of liquid crystalline properties that explain the reasons for their wide application. Next, the authors discuss how to explain these properties through the use of demonstration and laboratory experiments to students at various levels of education. Finally, they show how these complex properties are used in devices, and how these applications can be explained to students. Some results of testing the teaching module about liquid crystals are demonstrated and discussed.

INTRODUCTION

Students are familiar with modern technical devices like iPods, mobiles and several other devices that are based on liquid crystals and the properties that make them interesting for applications. Liquid crystal is a common name for a material, which possesses an additional phase between the crystalline and the liquid phases, that has the properties of both crystals and liquids. The phase is called the liquid crystalline phase [1]. What makes liquid crystals and their liquid crystalline phase so special?

In this contribution, the authors discuss basic properties of liquid crystals on which the technology of everyday devices is based from the education point of view. They have two main properties: the birefringence found in the liquid crystalline phase and the easy manipulation of liquid crystalline structures with the external fields like electric field or surfaces. Academic research is focused mainly on finding materials or improving existing materials with liquid crystalline phases having stable structures, which could be easily manipulated by external fields and have short recovery times when externally applied conditions are changed.

The role of liquid crystals in education is different. As they are materials with peculiar properties, students meet every day but are usually not aware of their existence, the topic might be interesting and motivating for them. If experiments are designed in a way that allows students to gain a deeper understanding of the phenomena on which applications are based, it is believed that the active way of teaching may also increase their motivation. Therefore, a short overview of experiments is also presented.

Finally, the authors report briefly on the knowledge obtained informally, as the topic is not a part of regular curricula, and some preliminary results on responses of students to whom the topic was introduced have been included.

LIQUID CRYSTALS AND THEIR PROPERTIES

Liquid crystals are crystals at low temperatures. During heating, they become a milky liquid having rather high viscosity at a cer tain (transition) temperature. If heated further, they become a transparent liquid at some higher temperature, which is usually called a clearing point. The appearance of the three phases of the liquid crystal called MBBA (*N*-(4-Methoxybenzylidene)-4-butylaniline) can be seen in Figure 1. Liquid crystals that are mostly used in displays are formed from elongated molecules. For presentation purposes, they are usually presented as ellipsoids, which are positionally and orientationally ordered in the crystalline state (Figure 2a), and positionally and orientationally disordered in the isotropic liquid state (Figure 2c). The liquid crystalline phase, which is found between the two phases consists of several domains, where molecules are on average oriented in different directions. The severe scattering of light on interfaces between domains is a reason for milky appearance.

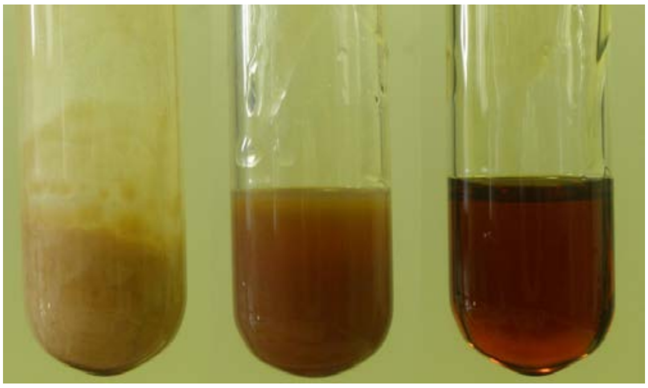
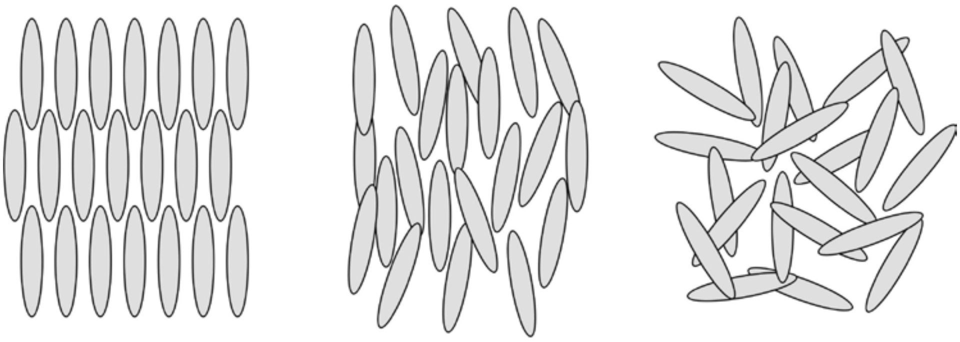


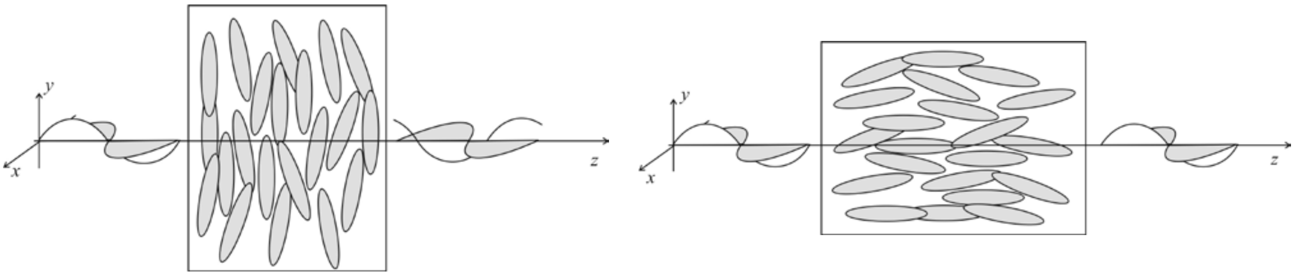
Figure 1: MBBA in three different states: the crystalline, the liquid crystalline and the liquid state. The temperature in each test tube is different; they were put side by side for the illustrative purposes.



(a) (b) (c)

Figure 2: a) The structure of the crystalline phase, b) of the liquid crystalline phase (nematic phase); and c) of the isotropic liquid phase. Figures a) and b) show the structure of one domain only.

Let us focus on the liquid crystalline state in the continuation. There are several liquid crystalline phases. The phase, which is mostly used in displays is the nematic phase, where molecules are only orientationally ordered. Descriptions of other phases can be found in an extensive literature reporting liquid crystals [1]. To understand the principles, on which displays technology is based, one has to consider the transmission of light through the nematic liquid crystal. Elongated molecules have different polarisabilities along the long molecular axis, then, perpendicularly to it. If long molecular axes are ordered such as in nematic liquid crystalline phase (Figure 2b), the light, which is polarised along the average orientation of long molecular axes, has a smaller velocity than the light polarised perpendicularly to this direction. The polarised light beam splits to two perpendicularly polarised beams having different velocities and, consequently, different refraction indexes (see Figure 3).



(a) (b)

Figure 3: a) The light polarised perpendicularly to the long molecular axes passes the material having different phase shift than the light polarised parallel to the average direction of the long molecular axes; b) If all polarisations are perpendicular to the long molecular axes, all polarisations have the same phase shift, and the polarisation state remains the same.

As the two perpendicularly polarised beams are phase shifted, the light is elliptically polarised in general. Therefore, the light can be transmitted through crossed polarisers, if an anisotropic material is found between them. Even more, the state of order, its magnitude and its direction, can easily be manipulated by external electric field. When the nonpolar molecules are found in an external electric field, they polarise and their polarisation is proportional to the external electric field. A torque acts on a polarised molecule in an external electric field, and molecules tend to orient in the direction of the electric field. The torque depends on the electric field quadratically (Figure 4).

$$\vec{M} = \vec{p}\times\vec{E};\ \ \vec{p} = (\chi_E - 1)\varepsilon_0\vec{E};\ \ M = (\chi_E - 1)\varepsilon_0 E^2 \quad (1)$$

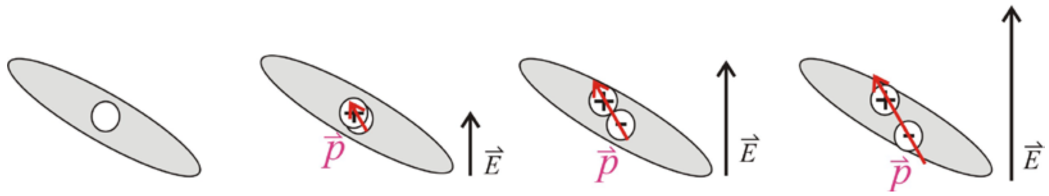


Figure 4**:** Nonpolar molecule becomes polarised in an external electric field. Due to its elongate shape, its induced dipole moment does not coincide with a direction of the external electric field.

Using the external electric fields of few volts applied on the cell only, one can reorient long molecular axes and significantly change the state of the transmitted polarised light. Because the direction of the molecular orientation is arbitrary, one also has to provide the returning mechanism into the initial state. This mechanism is provided rather simply by gently rubbing the surface of the glass plates with velvet. The treatment has two consequences. All molecules orient in a single direction defined in advance by the direction of rubbing. The system does not have domains, therefore, the liquid crystalline material is transparent when it is found in the cell prepared in this way. Next, due to the treatment any direction of long molecular axes is no longer equivalent. The molecules tend to be parallel with the glass surface and the rubbing direction. Molecules reoriented by an external electric field return this origin to their initial orientation when the external electric field is switched off.

The basic mechanism on which liquid crystalline displays are operating is the following: the elliptically polarised light is transmitted through the crossed polarisers and the oriented liquid crystal between them. The external electric field reorients the liquid crystal and acts like a shutter for the transmitted light. All the rest is details. The display has to be divided into pixels. Pixels have to be constructed with filters that change the white light into light having only colours, which allow for additional mixing. The electronics have to provide fast responses, etc. Technology behind the large TV screen is far from simple, but the basics have been discussed before. What is important and should be heard by students? They have to be aware that the liquid crystalline state is a special state of matter, which has anisotropic properties. These properties become evident when the liquid crystal is found in a cell with surfaces treated in a special way. If so, the liquid crystalline material has two refraction indexes. Anisotropic properties can be changed by the application of an electrical field.

LIQUID CRYSTALS IN SCHOOL

Mechanisms of the liquid crystal display were discussed in the previous section. As students do not have any practical experience with a d elicate state of matter called liquid crystals, it is more than welcome, if teachers provide such experience. Simple, hands-on type experiments are the most appropriate. The main problem is the material. There are two ways of obtaining it, synthesising it in the school laboratory [2] or purchasing it from the provider. The first needs good communication and the interdisciplinary coordination between the chemistry and physics teachers, who are usually not the same. The second possibility is problematic with respect to amount, as providers do not usually sell small amounts. However, if this problem is solved, several experiments are rather easy to perform: measurements of the transition temperatures, construction of the liquid crystalline cell, observation of the cell and the phase transition under a polarising microscope, double refraction on the wedge cell and, finally, the manipulation of the transmission by the applied electric field [3].

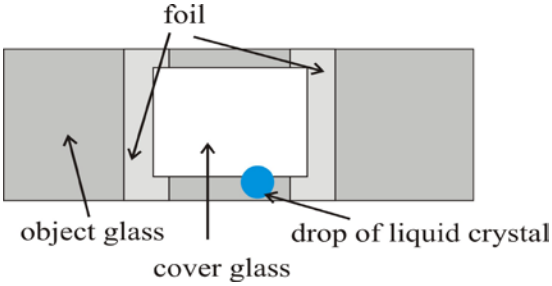
The Transition Temperatures

The liquid crystal has to be of the type that has both transition temperatures, i.e. the transition temperature from the crystalline to the liquid crystalline phase and the transition temperature from the liquid crystalline to the isotropic liquid phase, close to the room temperature. Examples are materials like MBBA and 5CB.

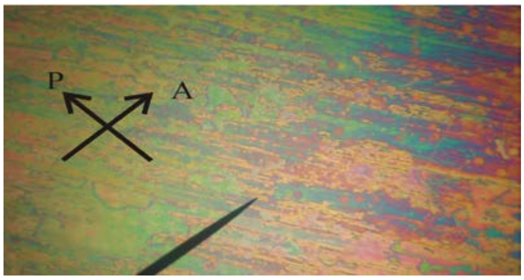
A test tube with the liquid crystal is left for few hours in a freezer or at least in icy water. These temperatures are low enough for the material to be in the crystalline phase. The test tube with the crystalline material is then placed in the water at around 0°C, which is slowly heated and its temperature measured. The crystalline phase starts to melt at around 20°C. The liquid crystalline phase appears as milky liquid, but it keeps this appearance at over twenty 20°C. At around 40°C, the second phase transition takes place and the milky liquid becomes a clear liquid. When the material is synthesised in the school laboratory, the transition temperatures can be used as a criterion for success of the synthesis. If temperatures are close to the temperatures given in references, then, the synthesis will be successful. Experiences show that only one group out of 16 was not successful in synthesis, although students were not students of chemistry.

The Birefringence and the Liquid Crystalline Cell

As mentioned before, the special property of transparent anisotropic materials is double refraction usually described by birefringence, which gives the difference between two refractive indexes for two polarisations in which the light beam is split. To observe the property, the liquid crystal has to be placed in a special container that will keep the uniform direction of the long molecular axes. Such a device is called a liquid crystalline cell, and is usually made professionally in clean rooms for scientific studies and for applications in devices. For teaching purposes, they can be made in a much simpler way. The microscope slide and the cover glass usually used for samples in microscopy are cleaned with alcohol and, then, rubbed in the same direction with velvet. To control the distance between glass plates, plastic foil used usually as a food wrapper or an adhesive tape is applied to both sides of the cover glass, and the cell is heated slightly by using a hair dryer. A drop of liquid crystal is put near the cover glass, then, it is heated enough to achieve the liquid state and by capillary action is sucked between the glass sheets (Figure 5a).



(a)



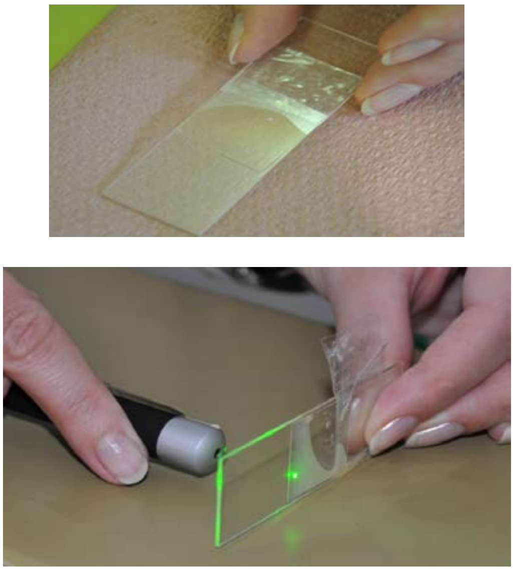
(b)

Figure 5: a) A sketch of the hands on construction of the liquid crystalline cell; b) The cell filled with the oriented liquid crystal in the liquid crystalline phase observed between crossed polarisers under the microscope.

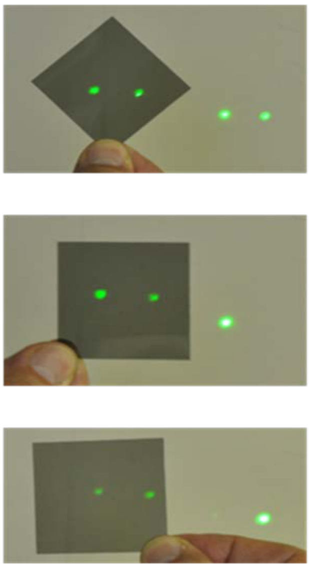
The thin cell filled with the liquid crystal is placed between two crossed polarisers. When long molecular axes are oriented in one direction only, the colours appear. Origins of the colours are discussed in detail in Reference [4]. They can be observed under the microscope (Figure 5b). In addition, if one heats the cell with a hairdryer, the transition to the isotropic phase appears and is recognised as the vivid entrance of black patches, which grow and cover the whole area, making it non-transparent.

Double Refraction

As said before, light beams split into two perpendicularly polarised beams when passing through an anisotropic material; for example, such as liquid crystal. The cells have to be narrow in order to sustain the unidirectional order. Laser pointers are usually used as light sources. The light beam is rather wide and both beams are still mixed after transmission. In order to obtain the space separation of the two beams, prismatic effect is used. When making a cell, instead of putting foil on both sides of the cover glass, only one side is covered with a few layers of foil. The other side of the cover glass leans directly on the microscope slide. Other steps in the production of the cell are the same (Figure 6a). The cover glass and the microscope slide now form a wedge and, when the cell is filled with the liquid crystal, it acts as a prism bending the two light beams according to their two different refractive indexes. On a distant screen, the light makes two light spots. As beams are perpendicularly polarised, the polarisation can be verified by a polariser (Figure 6b).



(a)



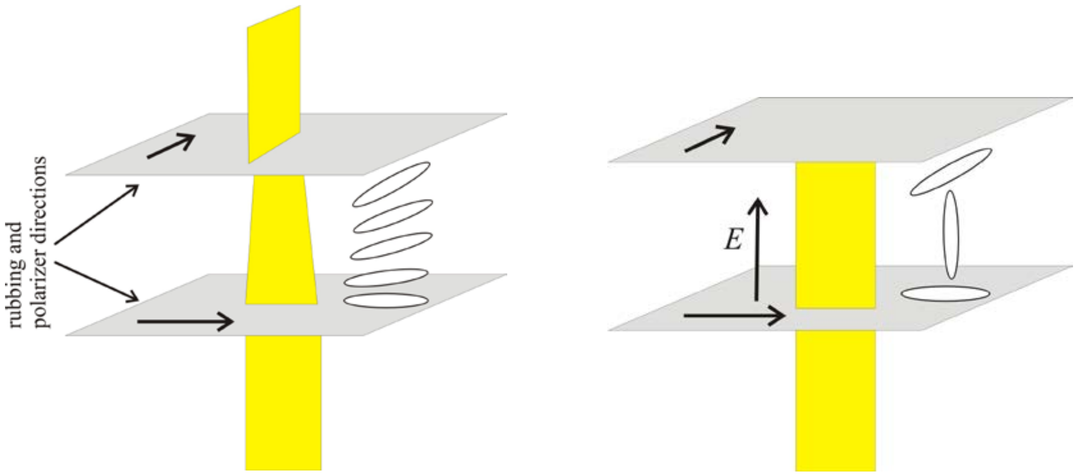
(b)

Figure 6: a) The light is transmitted through the wedge liquid crystalline cell; b) The two light spots are perpendicularly polarised.

Now, finally, to the last experiment, which is the easiest to perform but the most complicated with respect to material. One needs a cell that is covered with a thin layer of conductive material that can act as a capacitor. Such cells are often available from producers and can be bought. The cell presented here is a cel l that was discarded due to defects; however, for teaching purposes is more than adequate. The cell is placed between crossed polarisers and by applying few volts, it switches the cell between the transparent and dark states (Figure 7), similar to the way the display works.

DISPLAYS

How displays work will now be briefly explained. The nematic liquid crystal is between two glass plates that are rubbed in perpendicular directions (arrows in Figure 7). This causes the competition between influences of the two rubbing directions and the molecules adapt to it by forming a helix. If the light polarised in the rubbing direction enters such a cell, its polarisation follows the orientation of molecules and rotates for 90° when it arrives at the opposite surface. As the polariser direction is also perpendicular to the polarising direction on the opposite side, the light beam is transmitted. This presents the bright state. If the electrical field is applied, molecules in the middle of the cell orient along the electric field, and the polarisation of the transmitted light does not rotate when passing through. As the polarisation of light is now perpendicular to the polariser direction, it is absorbed. This presents the dark state. The grey states are achieved by applying smaller fields; however, the technology of better grey states is still a current research and development problem. Colour are obtained by colour filters that form pixels. The whole technology of addressing pixels, which have to be addressed separately for each colour, is something that goes beyond this contribution.



(a) (b)

Figure 7: a) Due to different rubbing directions above and below, the direction of molecular order is twisted. The light also changes its polarisation direction and is transmitted; b) Electric field reorients the long molecular axes and the light preserves its polarisation state. Therefore, it is absorbed in the polariser above.

PREKNOWLEDGE OF STUDENTS

A study on the informally obtained knowledge on liquid crystals prior to the university education has been conducted. 448 pre-service teachers participated in the study by completing a 20-item paper-pencil questionnaire. All participants were first year university students and the study was carried out at the beginning of the school year. Since liquid crystals are not taught in primary and secondary schools, it can be assumed that the knowledge tested was the knowledge obtained through informal education prior to the university level studies [5].

From the analysis of students' answers, the following results were obtained:

1. 22% of students listed a product with liquid crystals (the most common answer was LCD, other correct answers were LC thermometer, welding goggles, bulletin boards, jewellery);
2. 29% of students recognised one property of liquid crystals (out of three), which is important for applications (22% of students knew the importance of optical properties; 18% of students were in error, thinking that the density of liquid crystals is the crucial property);
3. 6% of students answered that there are more than three states of matter;
4. 30% of students knew, or guessed, that the liquid crystalline state is one of the states of matter;
5. 10% of students correctly sketched the distribution of molecules in the liquid crystalline state;
6. 18% of students thought that liquid crystals also occur in living organisms.

The final conclusion of the study is that despite the fact that liquid crystals are common in everyday life, students have very limited knowledge about them. Most of the students who had heard about liquid crystals related them to liquid crystal displays. Female and male students gained a statistically different average number of points in their responses to the questionnaire. Students who self-assessed their knowledge about liquid crystals as good, also gained statistically significantly better results than students who self-assessed their knowledge as negligible. There is also a statistically different achievement among students in the different fields of study programmes.

CONCLUSIONS

Liquid crystals can be seen every day everywhere, but they are not known and consequently not recognised. It is believed that the introduction of liquid crystals into school can be interesting, welcome by students and presents a topic which is related to students' everyday experiences.

In this paper, the authors discussed the properties of liquid crystals, presented several hands-on experiments for demonstration of these properties, briefly showed how a prototype liquid crystal display works and finally discussed the present knowledge of students with respect to liquid crystals. This paper may also serve as a motivation for the introduction of prototype LC cells in the teaching of technological subjects and for construction of model displays.

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