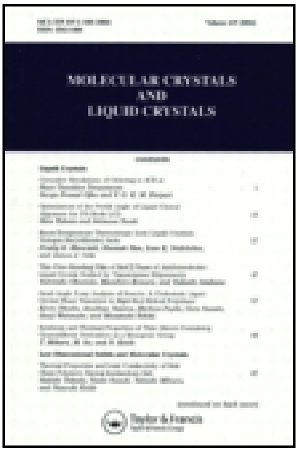

Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl20

Teaching Liquid Crystals with a Wood Model

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Version of record first published: 16 Jun 2011

To cite this article: Saša Ziherl, Katarina Susman, Jerneja Pavlin, Jure Bajc & Mojca Čepič (2011): Teaching Liquid Crystals with a Wood Model, Molecular Crystals and Liquid Crystals, 547:1, 241/[1931]-248/[1938]

To link to this article: http://dx.doi.org/10.1080/15421406.2011.572528

Mol. Cryst. Liq. Cryst., Vol. 547: pp. 241/[1931]–248/[1938], 2011

ISSN: 1542-1406 print/1563-5287 online
DOI: 10.1080/15421406.2011.572528

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Teaching Liquid Crystals with a Wood Model

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The uniaxial symmetry in the liquid crystalline phase leads to anisotropy in many physical properties. A simple look on a piece of wood reveals that also its structure is anisotropic. It has also strong anisotropic dielectric properties in the microwave range, like liquid crystals in the visible range. Therefore the wood can serve as a model for demonstration of anisotropic optical properties in liquid crystals. Experiments for more illustrative explanation of the anisotropic properties are presented. As wood is transparent for microwaves, many anisotropic properties can be illustrated experimentally, using a simple school microwave kit.

Keywords Anisotropy; birefringence; liquid crystals; microwaves; optical rotation; wood

1. Introduction

Many people are aware that liquid crystals are present in displays, phones, laptops… Despite the fact that liquid crystals are quite common in everyday life, a recent research showed that students' conceptions about liquid crystals are very weak [1]. Therefore it seems important that students get the right conceptions about liquid crystals and their anisotropic properties, so they could understand how technological systems work.

Using analogies and visualisation during teaching physics is usually very helpful for students' understanding. As the structure of wood is clearly seen and is in general anisotropic, the wood can serve as a model for demonstration of anisotropic optical properties in crystals in the visible region. Therefore experiments for more illustrative explanation of the anisotropic properties (e.g., birefringence and linear dichroism) were developed [2].

The aim of this paper is to present the analogies between liquid crystals and wood. Two wood models are presented. First model is meant to demonstrate analogy with nematic liquid crystals and the second with cholesteric liquid crystals.

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2. A Model for Nematic Liquid Crystals

A simple look on a piece of wood reveals that its structure is anisotropic (Fig. 1). One can easily see annual rings and wood fibres, which are nearly parallel, and identify three orthogonal directions with different mechanical and also dielectric properties. One is directed along the wood fibres, one is perpendicular to the layered annual sheets and the third is perpendicular to these two directions. Although there is pronounced mechanical anisotropy in these three directions, orientation of the fibres plays the most important role in dielectric properties [3]. Therefore uniaxial symmetry is expected in experiments with electric field and wood fibres are indicators for the direction of the molecules.

A nematic phase structure of liquid crystals has one or two molecular axis oriented parallel to one another, resulting in an orientational long-range order (Fig. 2). Molecular long axes parallelism results in intrinsic optical anisotropy (double refraction) [4].

So if one compares wood structure with a liquid crystal's structure, one can find a similarities in both structures. The difference is that the structure of wood is easily seen with no special equipment, but about liquid crystal's structures one can only conclude from macroscopic properties or observations [5,6].

2.1. *Order Parameter*

The value of the order parameter of wood is much higher as it is in nematic liquid crystals. It can be easily measured and calculated by using a ruler and a pen. The procedure is similar to the measuring of order parameter of dropped toothpicks

Figure 1. A piece of wood appropriate for measurements. (Figure appears in color online.)

Figure 2. Molecules in a nematic liquid crystal. (Figure appears in color online.)

which is described in [7]. The equation for the order parameter of wood "molecules" is the same as it is for liquid crystals molecules

$$S = \frac{1}{2}\langle 3\cos^2\theta - 1\rangle, \tag{1}$$

where θ is the angle between the molecular axis and the local director (which is the 'preferred direction' in a volume element of a sample, also representing its local optical axis). The direction of wood molecules is the direction of wood fibres. The order parameter of spruce wood used for the measurements is around 0.9.

2.2. *Birefringence*

Nematic liquid crystals are birefringent, so they have two refractive indices, one for polarization parallel and one for polarization perpendicular to the optical axis. When a linearly polarized light passes through nematic liquid crystal, it becomes in general elliptically polarized. Similar effect is observed when microwaves pass through a piece of wood. As wood structure is anisotropic, an electric field applied parallel to the fibres is expected to induce different response than an electric field applied perpendicular to the fibres. Refractive indices and also absorption coefficients for polarizations parallel and perpendicular to the wood fibres differ, so the linearly polarized incident wave becomes elliptically polarized after transmission through the wood.

The experimental setup is seen in Figure 3 and its geometry is seen in Figure 4. One is allowed to rotate separately the transmitter and the receiver. For measuring the birefringence, the angle between transmitter and wood fibres is fixed and set to 45° ($\beta = 45°$). Microwave transmitters emit polarized microwaves and the receivers detect only the component of the microwaves polarized in one specific direction. Therefore, the polarizer and the analyzer in Figure 4 are considered symbolically as indicators for the direction of the incident microwave polarization and for the detectable polarization of the receiver respectively. The transmitter used emits

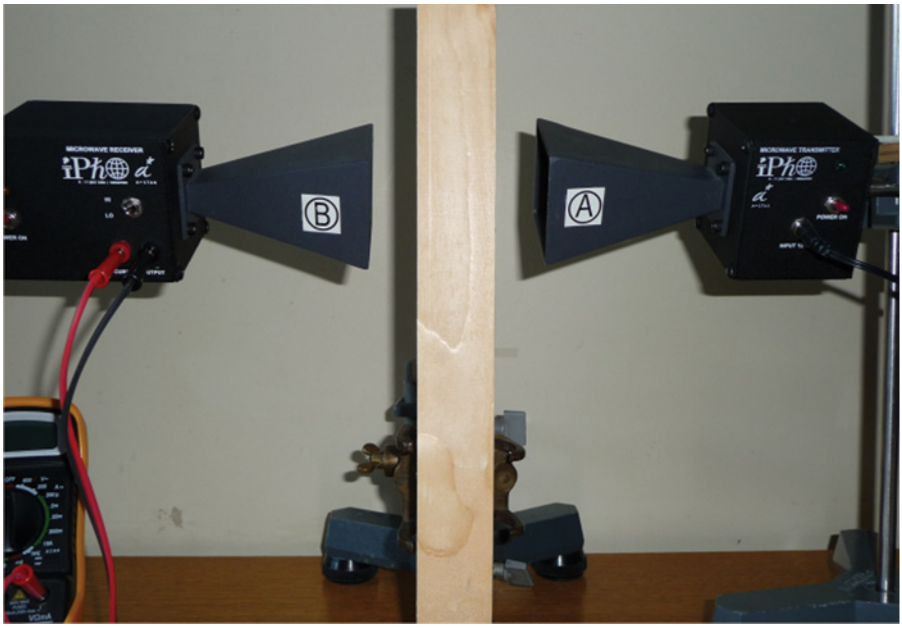

Figure 3. The experimental setup. Right instrument is microwave transmitter (polarizer), left instrument is microwave receiver (analyzer) and wood sample is in between. (Figure appears in color online.)

microwaves with wavelength 2.8 cm. Measured current is proportional to the amplitude of the electric field. Samples of wood were three spruce boards with different thicknesses.

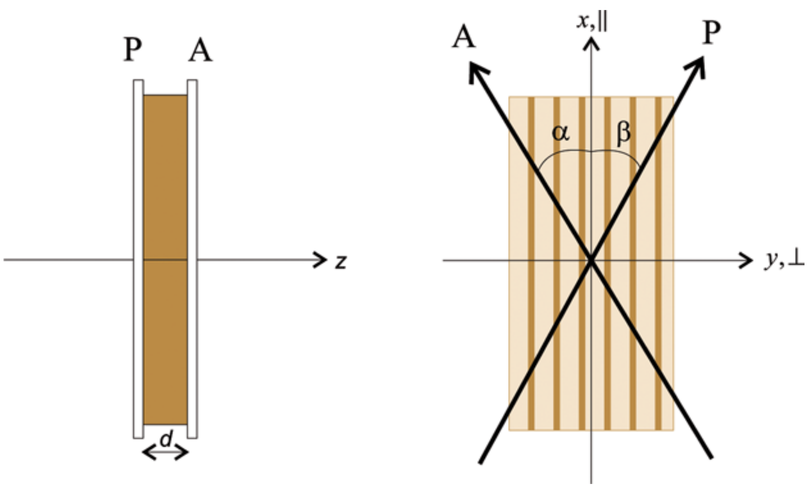

Figure 4. Side view (left): Microwaves propagate along z axis, wood thickness is d, letters P and A denote polarizer and analyzer. Direct view (right): Arrows denoted by P and A show the transmission direction of polarizer and analyzer. (Figure appears in color online.)

The expression for the intensity of the transmitted microwaves is similar to the expression for the intensity of light after interacting with a nematic liquid crystal. For the transmission through the wood, the anisotropy in refractive index as well as in absorption, have to be included in the analysis. Therefore the intensity for the transmitted electromagnetic wave is

$$I = \frac{1}{2}\varepsilon_0 c E_{0A}^2$$
$$I = \frac{1}{2}\varepsilon_0 c E_0^2 \Big(e^{-2\lambda_{\|} d} \cdot \cos^2\alpha \cdot \cos^2\beta + e^{-2\lambda_{\perp} d} \cdot \sin^2\alpha \cdot \sin^2\beta - \frac{1}{2} e^{-(\lambda_{\|}+\lambda_{\perp})d} \cdot \sin 2\alpha \cdot \sin 2\beta \cdot \cos\delta \Big) \quad (2)$$

where E_0 is the amplitude of the electric field of the out coming microwave, α and β are the angles defined in Figure 4, $\lambda_{\|}$ and $\lambda_{\perp}$ are the absorption coefficients for parallel and perpendicular polarization, d is the thickness of the wood and δ is the phase difference between the microwaves polarized parallel and perpendicular to the wood sample. Phase difference is defined as

$$\delta = \frac{2\pi(n_{\|} - n_{\perp})}{\lambda_0} d, \quad (3)$$

where $n_{\|}$ and $n_{\perp}$ are refraction indices for microwaves polarized parallel and perpendicular to the wood sample, respectively, and λ_0 is the wavelength of the microwaves in the air.

The experimental results for spruce wood of three different thicknesses are shown in Figure 5 [2]. The measurements confirm that microwaves become

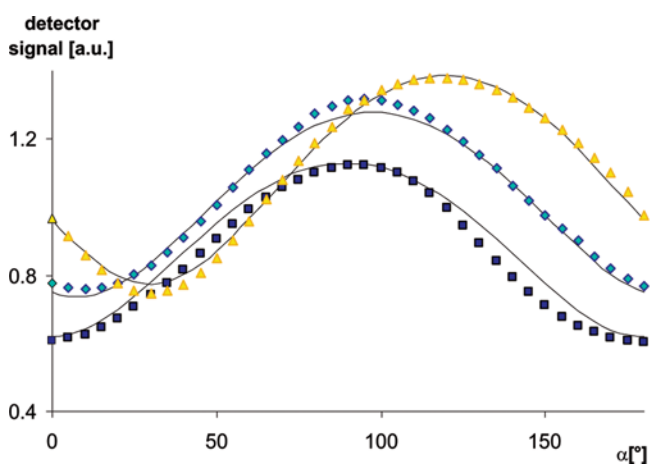

Figure 5. Dependence of measured intensities on the angle between analyzer and wood fibres for three thicknesses of spruce wood (squares – 5.3 cm, diamonds – 4.6 cm, and triangles – 3.4 cm). The polarizer is rotated 45° ($\beta = 45°$) with respect to fibres. The fit of these measurements according to Eq. 2 is given by solid curves [2]. (Figure appears in color online.)

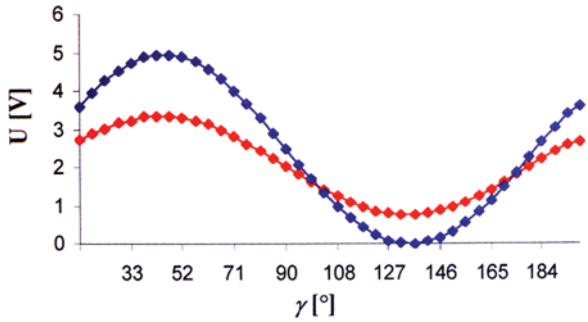

Figure 6. Dependence of measured current on the angle between analyzer and polarizer. Blue dots – without liquid crystalline cell, red dots – with liquid crystalline cell [9]. (Figure appears in color online.)

elliptically polarized after transmission through the wood. One can determine the birefringence value ($\Delta n = n_{\parallel} - n_{\perp}$) by the minimization of the difference between the observed and theoretical intensities (Fig. 5). The birefringence value for spruce wood according to our measurements is around 0.15, which indicates a relatively large anisotropy. For example, liquid crystals, which are known to have very large birefringence in the optical region, can have Δn up to 0.3 [8]. If the results obtained with the microwaves and wood are compared to the experiments of light interacting with a nematic liquid crystal (Fig. 6) [9], one can see some resemblance between the results. In Figure 6 it is shown that if linearly polarized wave (blue dots) is sent through the wedge cell filled with a nematic liquid crystal, the wave becomes elliptically polarized after transmission through the cell (red dots).

3. A Model for Cholesteric Liquid Crystals

The second model is based on the article of Gerritsen and Yamaguchi [10]. They presented an experiment, which is meant to demonstrate an analogue of cholesteric

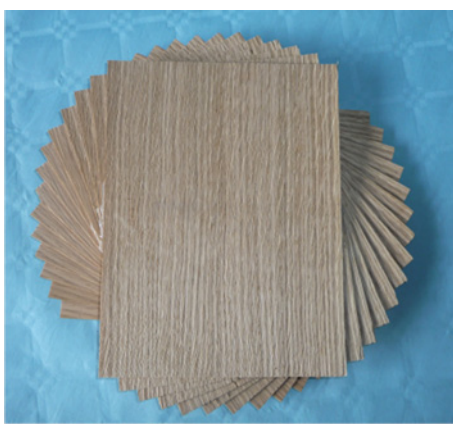

Figure 7. A twisted wood model made from oak sheets. Every consecutive sheet is rotated for a fixed angle regarding to precedent sheet. (Figure appears in color online.)

Figure 8. Molecules in cholesteric liquid crystals. (Figure appears in color online.)

liquid crystals. The model consist of a series of thin plastic sheets to which copper wires are attached of dimensions small compared to the microwave length. The direction of the wires on successive sheets varies in a screw type fashion. Each thin plastic sheet with a parallel wires acts for microwaves as a wire-grid polarizer. Electric field components parallel to the wires are absorbed and the transmitted wave has an electric field purely in the direction perpendicular to the wires. This is the reason why these sheets are, as they say, »anisotropic« to the microwaves. The cause for rotation of microwave polarization (optical activity and rotatory power) in this experiment is absorption, and not anisotropy, like in liquid crystals, so the analogy is rather vague. Therefore a wood model was constructed which allows for better analogy for explanation of cholesteric properties.

In [10], the cholesteric liquid crystals are pictured as an ensemble of chiral molecules in a series of planes with their anisotropy directions more or less parallel in one plane, while in successive planes this direction changes by a small angle, creating a helical arrangement of the optical axis (Fig. 7). The twisted structure of cholesterics

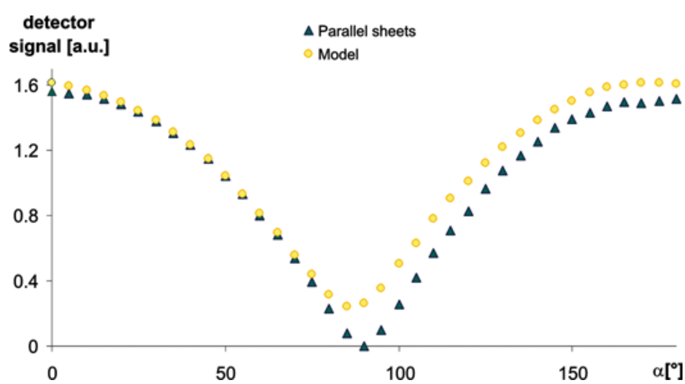

Figure 9. Dependence of measured intensities on the angle between analyzer and wood fibres for sample with parallel wood sheets (blue triangles) and for twisted wood model (yellow circles). The transmitter was parallel to the wood fibres (in second case parallel to the fibres from the first sheet). (Figure appears in color online.)

is the reason for several unique optical properties, namely, extremely high optical activity, selective reflection of circularly polarized light, etc. [4].

The molecules forming the fibres in wood are also chiral as they contain DNA. However, molecules are much smaller than the wavelength of microwaves and observable effects of their chirality are negligible as it is shown in [2]. Our twisted wood model is a set of thin wood sheets, where each successive sheet is rotated by a fixed angle with respect to the preceding sheet, so that the total structure shows screw-type symmetry (Fig. 8).

The experimental setup is similar to the first one (Fig. 3). The polarizer is set to 0° ($\beta = 0°$) according to the first sheet and the analyzer is rotated. Measurements were made with 10 oak sheets. The results of the measurements are presented in Figure 9. The blue dots present measurements with parallel sheets (they act like a normal piece of wood) and it can be seen that the received signal falls to zero at angle 90° (when the polarizer and analyzer are crossed). This is a clear sign of the absence of circular anisotropy. The yellow dots present measurements with the model of a cholesteric. The received signal does not fall to zero and minimum is also shifted according to previous measurements, so this twisted wood model shows optical rotation (circular dichroism and optical activity are due to the twisted structure).

4. Conclusions

Microwaves and wood provide a better visualisation to students when teaching about liquid crystals and their anisotropic properties. Wood and microwaves offer an ideal system where anisotropy is easily understood. We have presented analogies between wood in the microwave region and liquid crystals in the visible region. These experiments with a microwave transmitter and receiver can easily be done in schools for demonstration purposes or as laboratory work.

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