On the Colours and Patterns created by Shards of Cellophane

Several teachers have asked why the insertion of 'Cellophane' sheets between the liquid crystal shutter and the top polariser creates colours and why these change in response to an AC voltage being applied to the LC shutter.

For pupils it should suffice to tell them that the 'Cellophane' has an unusual optical property (called birefringence*) that causes the different colours, in the white polarised light emerging from the shutter, to be altered/rotated by different amounts, so that some colours pass more easily through the top polariser than others. Rotating the top polariser by 90 degrees reverses this so that a complementary colour is seen in each area. Applying a voltage to the LC shutter does this without requiring a mechanical rotation and also allows other colours to be seen at voltages between those for ON and OFF. These drive voltages can be obtained from the output of an audio amplifier, so that the patterns then respond to the music, or speech, generating the audio signal.

Should you wish to know more about this, a more detailed explanation can be found in the edited patent extracts below.

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* A birefringent material has a preferred direction, such as the stretch direction in a polymer film like cellophane, and light polarised along this optic axis travels at a different speed through the film from light polarised orthogonal to this axis. Typically, such a birefringent material has two refractive indices: an extraordinary refractive index n_e for the former and an ordinary refractive index n_o for the latter. The birefringence of the material $\Delta n = n_e - n_o$.

Any polarised wave can be resolved into component waves polarised along this optic axis and transverse to it and, since these travel at different speeds, the polarisation of the emergent wave depends on their amplitudes and their phase difference (also called the optical retardation, δ, of the sheet). This phase difference depends on Δn, on the thickness of the film and also on the colour (wavelength) of the emergent light and, thus, so will the polarisation. Passing the emergent light through an analysing polariser, therefore, causes different wavelengths to be more, or less, strongly absorbed and colours to be observed.

Extract from Patent GB1469638

Inventor: Shanks, Ian A.
Filing Date: 18/07/1973

In a liquid crystal device a cell is formed by enclosing a layer of a liquid crystal material between two glass plates. One such cell is known as the twisted nematic cell. In the twisted nematic cell plane polarised light passing through the cell is rotated by an amount determined by the relative angular alignment of liquid crystal molecules at the interfaces with the glass. Orientation of molecules is achieved by a rubbing of the glass surface. Typically a twisted nematic cell is arranged to rotate polarised light by 90° although rotation by other angles may also be obtained. Application of a suitable voltage to the liquid crystal layer (via transparent electrodes) causes the molecules in the layer to align themselves parallel to the applied field so polarised light passes through without rotation.

An object of this invention is to provide colour changes in a liquid crystal device.

According to this invention a liquid crystal device includes a liquid crystal cell capable of rotating plane polarised light, at least one layer of a birefringent material arranged parallel to the cell, a polariser also arranged parallel to the cell, and means for applying a variable voltage across the liquid crystal cell whereby polarised light passing through the device may be observed to exhibit colour changes.

The birefringent material may be one or more layers of cellulose film (e.g. `Cellophane`), polyvinyl alcohol film, or polyvinyl fluoride film.

A thin film of optically transparent birefringent material, such as cellulose film (`Cellophane`), can give rise to vivid colours when placed between polarisers. This effect is maximised when the polarisers are at 0° or 90° relative to each other and when the optical axis of the birefringent film is at 45° to one of the polarisers. Under these conditions it is possible to produce two distinct hues by rotating one of the polarisers through 90°. These hues are generally related e.g. blue and yellow, green and magenta, red and cyan. Different or multiple thicknesses of the birefringent film give rise to different such colour combinations provided that, when multiple thicknesses are utilised, the optic axes of all the layers are parallel to one another and at 45° to one of the polarisers.

If the optic axes of adjacent birefringent layers are non-parallel, then rotation of either the polariser or the analyser through 180° can give a continually varying series of colours. In all cases the actual colour obtained in a given situation depends on the optical retardations of the various sheets and can be varied by rotating the polariser or analyser. All cases can be calculated by a simple, if lengthy, application of the mathematics of anisotropic optics known in the art.

The theoretical basis for calculating the colours to be observed is as follows:

When one birefringent layer is used the transmission of the device to unpolarised light is given by $T=1/2\cos^2(\alpha-\beta)-1/2\sin 2\alpha \sin 2\beta \sin^2(\delta/2)$

where α and β are the angles between the polariser and analyser transmission axes respectively and the optic axis of the layer, and δ is the optical retardation of the layer given by $\delta=(2\pi/\lambda)\Delta nt$

where

$\Delta n=n_e-n_o$

t=thickness

n_o=refractive index of the ordinary wave

n_e=refractive index of the extraordinary wave.

When a composite layer, having n sheets of optical retardation δ, is used then the transmission of the device becomes, in general, a polynomial of order 2n in $\cos\delta$. Thus

$$T = \left[\sum_{r=o}^{n} a_r \cos^r\delta\right]^2$$

where the coefficients a_r depend on the angles of the polariser, the analyser and the optic axes of the n sheets relative to some fixed datum.

The voltage applied to the cell across the liquid crystal layer may be A.C.† square or sinewave of frequency up to about 100 kHz; the untwisting effect responding to the RMS value of the A.C. voltage above about 20 Hz.

Extract from Patent GB1470523

Inventor: Shanks, Ian A.
Filing Date: 07/08/1973

According to this invention a liquid crystal colour display device comprises a polariser and analyser arranged on a common optical path, an electro optic liquid crystal cell arranged on the optical path between the polariser and analyser and capable of rotating the plane of incident polarised light through an angle which is a function of a voltage applied thereto, a composite layer of birefringent material arranged in a desired pattern on the optical path between the polariser and analyser, and means for applying a modulated voltage to the cell whereby on transmission of light along the optical path the pattern may be observed to exhibit changes of colour with a change of voltage.

† DC voltages can cause electrolysis in the liquid crystal or the transparent electrodes and are not used.

The composite layer may comprise a number of shaped pieces of birefringent material arranged on top of one another with various orientations of their optic axes to provide various thicknesses across the composite layer. In addition the shaped pieces may have different or variable thicknesses and may be made from different birefringent materials. The actual colours observed depend upon the birefringence of the material, its thickness and the orientation of its optical axis. The modulated voltage may be a sound modulated voltage or a cyclically modulated voltage.

The pattern is seen having different colours dependent upon the voltage applied to the cell. Thus the patterned display will change colours in response to the sound variation from e.g. a vocal or instrumental group or from a sound recording. This pattern may conveniently be projected on to a suitable surface in a dance hall or discotheque for example, or viewed using a magnifying or other viewing device. The device can be made into a suitable size for insertion in a projector. A number of devices may then be illuminated in sequence to display different patterns and colours in time to the music. The device may be incorporated in a fibre-optic lamp at the base of the fibres so as to produce a colour pattern on the ends of the fibres which changes in response to the voltage waveform applied to the cell.