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ELECTRO-OPTIC SHUTTERS AND FILTERS

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The applications of liquid crystals in perceptual research are examined.

Introduction

The psychologist and the visual scientist often need a rapid and silent means of interrupting or attenuating light. By using fluorescent lamps, glow-modulator tubes, light-emitting diodes, electroluminescent panels or cathode-ray tubes, it is sometimes feasible to modulate the light source: but often, because the light must be very intense or because particular spectral bands are required or because the stimulus is complex or naturalistic, an independent shutter or filter is needed. Mechanical shutters may not offer the requisite speed or silence; and their vibration may disturb other optical components, such as pellicles. An opaque vane, or a very small mirror, mounted on a galvanometer or a stepping motor, may be fast and almost noiseless, but can be used only when the aperture is small (in a Maxwellian-view system, for example, where small images of the light source are formed).

In the hope of finding a further solution to this recurrent and very general problem, we have examined the potential of materials of the class known as liquid crystals. The optical properties of some of these materials may be altered by the application of electric fields. We describe the principles, the advantages, and the limitations of liquid crystal devices, and offer a guide to their use.

Liquid crystals

The liquid crystalline state is intermediate between the crystalline and liquid states in the degree to which molecules are arranged in an ordered structure. About 0·5 % of all organic compounds can assume this *mesomorphic* state over some range of temperatures and such compounds are characterized by long rod-shaped molecules. Within small volumes of the liquid crystal the molecules tend to align themselves with their longitudinal axes parallel, but these ordered arrangements are thought to be confined to local regions and the local structures may still flow relative to each other.

The three classes of liquid crystal, smectics, nematics, and cholesterics, are distinguished by further details of their molecular arrangement. The *smectic* state is the most ordered, the molecules being arranged in layers one molecule thick and the longitudinal axes of the molecules being perpendicular to the planes of the layers [Fig. 1(a)]. The distribution of molecules within any layer may be random or highly ordered, depending on the compound, but in either case the layers can slide easily with respect to one another. In the *nematic* state [Fig. 1(b)] the molecules are not arranged in layers; they move freely relative to each other with the restriction that they retain their mutually parallel orientation. In the *cholesteric* state the molecules are again arranged in layers, but the longitudinal axes of the molecules are now parallel to the planes of the layers and the distribution within any one layer resembles the nematic arrangement. Each layer is very thin (of the order of 0·5 μm) and successive layers are slightly rotated, giving a helical progression about an axis perpendicular to the planes of the layers [Fig. 1(c)]. The rotation is of the order of 15 min of arc per layer.

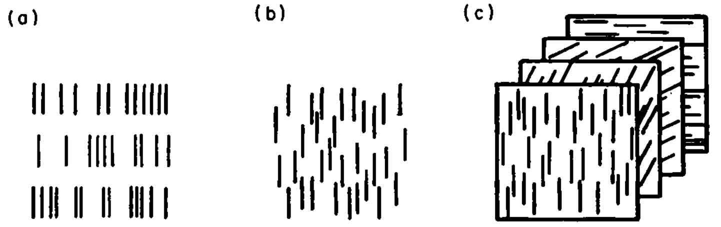

FIGURE 1. The molecular arrangements of the three types of liquid crystal. (a) Smectic; (b) Nematic; (c) Cholesteric.

The molecular alignment of a liquid crystal, and thus its optical properties, may be influenced by an externally applied electric field; and electro-optic effects of this kind provide the basis for the devices described below. The application to a liquid crystal of an electric field may force the molecules to lie with their longitudinal axes either all parallel to or all perpendicular to the applied field (depending on the dielectric constants of the particular compound). Owing to the intrinsic order of liquid crystals, this alignment occurs at field strengths well below those that would be needed to align independently-acting molecules.

Liquid-crystal shutters are typically prepared by sandwiching a thin film of a particular material between two glass plates, the inner sufaces of which have been coated with transparent electrodes. Gold, tin oxide, or indium oxide are usually used for the electrodes. The separation of the plates is of the order of 20 μm and is usually maintained by a thin mylar gasket.

For further details of the physics of liquid crystals we recommend the introductory reviews by Fergason (1964), Kirton and Raynes (1973) Soref (1973) and Shanks (1974), and the handbook edited by Gray and Winsor (1974). Williams (1975) provides a summary of US patents referring to electro-optic devices that use liquid crystals. Current developments are conveniently summarized in *Liquid Crystal Abstracts* (Locus Press, London). A particularly useful and comprehensive guide to the practical applications of liquid crystal devices is given in Tobias (1975). The classical ways of modulating light, and the several criteria by which a shutter should be judged, are discussed by Boynton (1967): the reader may wish to examine conventional solutions before turning to a liquid-crystal device.

We discuss below in detail two types of electro-optic cell of which we have had experience.

Phase-change devices

Shutters of this class are prepared from cholesteric materials. In the quiescent state the cell is not opaque but is milky and translucent; on application of an alternating field of high frequency it becomes clear and transparent. In many perceptual applications there is no disadvantage, but indeed a clear advantage, in the fact that the cell is not opaque in its off state: it will serve as its own adaptation field and the experimenter can pass transiently from a diffuse to a patterned stimulus with little or no change in the state of adaptation. The phase-change principle is described by Jakeman and Raynes (1971).

A few drops of cholesteric are sealed between two glass plates, of which the inner surfaces have been plated with a transparent electrode. The separation of the plates should be between 10 and 25 μm and should be constant across the area of the cell*. An active area of 50 × 50 mm is practicable. When an alternating field of high frequency and high voltage is applied across the cell, the molecules align themselves with their longitudinal axes parallel to the applied field. In this state the material resembles a nematic liquid crystal and is often referred to as a *pseudo-nematic*. Owing to its ordered structure, it is transparent. When the field is removed the cholesteric structure regrows, but this process occurs randomly at numerous centres throughout the film, a disorganized texture is produced, and light is scattered by the cell. (If no further field is applied, a single cholesteric structure will evolve in the course of days and thus the cell will become transparent.)

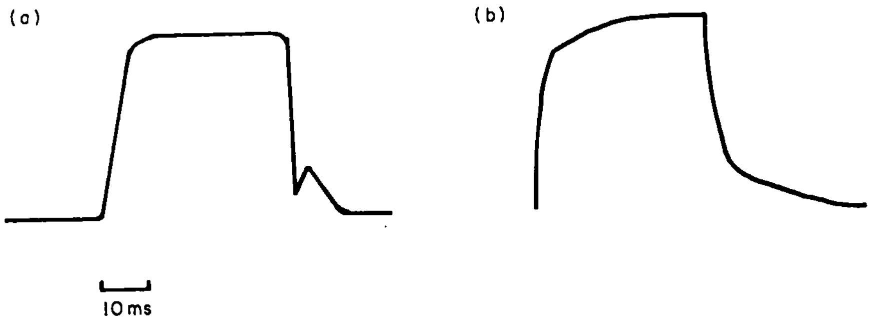

FIGURE 2. The time response of a phase change cell (a) and of a typical tachistoscope lamp (Sylvania F 6T5/D, "daylight") (b). The same time-interval generator and the same detector were used in making the two measurements. The output of the fluorescent lamp was unfiltered: the response would look still poorer if a yellow filter were interposed between the lamp and the photodiode.

A suitable voltage for a 20-μm cell is 200 V r.m.s. and the frequency should be between 1 and 100 KHz. It is important that the signal should have no d.c. component. The cell will pass from its translucent to its transparent state at a threshold voltage that varies with the separation of the plates but is of the order of 50 V r.m.s. However, although the cell will work at these low voltages, the time constant is long. The time constant becomes shorter in proportion to the square of the voltage, but eventually sparking will occur between the plates and leave permanent small imperfections in the cell. The time constant can be reduced by reducing the separation of the plates; but the break-down voltage is also thereby

* Cells of this type have been prepared for us by Phosphor Products Company Ltd., 10D Dawkins Road, Hamworthy, Poole, Dorset, BH15 4JB, U.K. Several cells are supplied for a minimum order of £50 (November, 1975).

reduced. We have typically recorded values of 5 ms for the rise time (fully off to fully on). The value of 30 μs reported in the physical literature is not to be taken seriously. The decay time depends on the properties of the cell itself and is independent of voltage: a typical value is 2 ms. The response of a phase-change cell is shown in Fig. 2. For comparison we show the response of a fluorescent lamp fitted to the 3-field tachistoscope described by Mollon (1970) and manufactured by Electronic Developments, Hampton, U.K.

We do not know the maximum life time of a typical phase-change cell, but we have subjected a cell supplied by Phosphor Products to 200 000 operations (5 Hz, 50 % duty cycle) without deterioration.

The special value to psychologists of the phase-change cell will be in applications where a diffuse field is replaced by a patterned one, a very familiar sequence in studies of human information processing. The cell can be thought of loosely as a ground-glass screen that can be switched on and off. Thus a single cell could serve as the basis for a cheap and compact one-field tachistoscope, an illuminated, patterned target being placed a little behind the cell. If the total flux reaching the eye is less when the cell is in its scattering state, then light from a second source can be thrown on to the cell from the observer's side so as to exactly equate (perhaps by direct flicker photometry) the adapting and stimulus fields. It is also possible to use the cell as a front- or back-projection screen and then to switch the screen on and off.

If less than complete extinction is acceptable, the phase-change device can serve as a conventional shutter. The attenuation obtained will depend on the geometry of the situation. Placing a cell in the collimated section of a Maxwellian-view system, we have measured an attenuation-ratio of 30:1 at the eye-piece. Cells could be placed in series to improve extinction. In the classroom we have found that phase-change devices served very satisfactorily to turn a pair of slide-projectors into projection tachistoscopes for the purpose of demonstrating apparent movement between complex patterns.

Twisted-nematic cells

Cells of this type are prepared from nematic liquid crystals*. In the resting state the cell has the property of rotating through 90 degrees the plane of polarisation of linearly polarised light. Application of a field abolishes this property. If, therefore, the cell is placed between two sheets of polarizing material, it can be arranged to transmit light in one state and interrupt it in the other [Fig. 3(a)]. The principle is described by Schadt and Helfrich (1970).

The twisted-nematic cell is prepared by rubbing, in perpendicular directions, the two inner surfaces of the glass plates from which the cell is to be constructed. When a film of nematic material is placed between the plates, the molecules of the layer nearest each rubbed surface arrange themselves so that their longitudinal

* We are very grateful to Mr W. Hopwood, of Pilkington Bros. Ltd., for providing us with a number of sample cells. A number of commercial sources are listed by Tobias (1975). Omni-Science Ltd., 43 Shakespeare Road, St. Ives, Hunts., PE17 4TT, U.K., act as consultants in this field. A single twisted-nematic cell should cost £15–£30; but most firms have a minimum order greater than this.

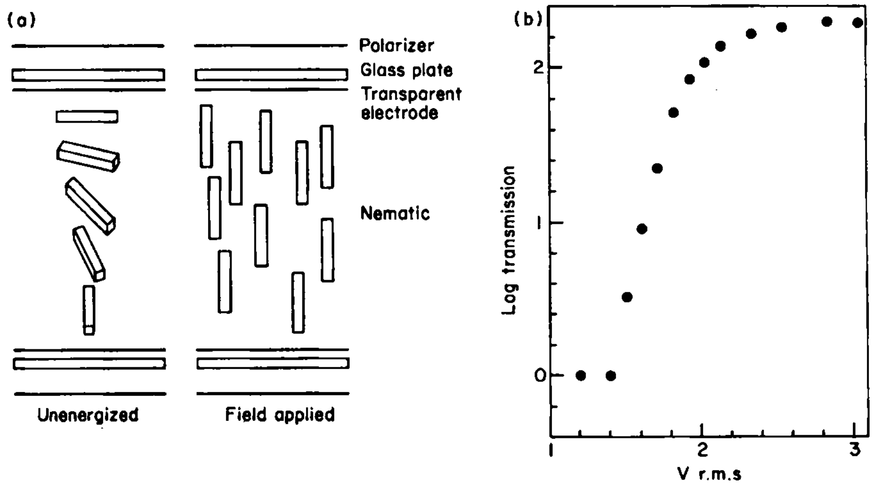

FIGURE 3. The twisted-nematic cell. Composition of the cell and principal of operation (a) Transmission as a function of applied voltage (b).

axes lie parallel to the direction of rubbing. The molecules of the intermediate layers take up intermediate orientations and so between the first and the last layer pass through a 90° twist. It is in this state that the cell has the capacity to rotate through 90° the plane of polarization of polarized light. Application of an electric field destroys the twisted organization: the molecules line up along the field and the cell no longer rotates the plane of polarization. When the field is removed the original organization is regained. Thus, if the cell is placed between crossed polarizers, the unit transmits light in the unenergized state and attenuates it in the energized state.

The voltage required is relatively low. For cells 12·5 μm thick we have found a field of 3 V r.m.s. at 2 kHz to be sufficient to operate the cell (a d.c. field will work, but will lead to deterioration of the cell). At an operating voltage of 18 V r.m.s. an onset time of 2 ms can be obtained, although the value of 100 μs predicted by Tobias (1975) is not obtained in practice. However, the disadvantage of the twisted-nematic cell as a shutter is its long recovery time: when the field is removed the cholesteric takes several hundred ms to recover its twisted organization.

We suggest below a way of using twisted-nematic cells to construct a fast shutter, but first describe the simpler case of its use as an electronically-controlled variable filter. As an increasing voltage is applied, the assembly of Fig. 3(a) does not pass immediately from full transmission to full extinction: Fig. 3(b) shows transmission as a function of voltage. The cell was placed between HN22 polaroids* in the converging beam of a Maxwellian-view apparatus and measurements were made with a silicon photodiode mounted at the eye-piece. We used a spectrally narrow band of yellow light with a peak wavelength of 575 nm and passed the beam through a 3 mm area of the cell. The extinction ratio was better than 200:1. (Poorer values

* Supplied by Polarizers (UK) Ltd., Lincoln Road, Cressex Estate, High Wycombe, Bucks HP12 3QU, U.K.

reported in the physical literature may be due to infra-red leaks during measurement.)

A variable filter of this kind would recommend itself where cheapness, compactness and silence were required. It is very easy to introduce the cell into a confined space in an optical system. It is noiseless and can be placed close to the subject's eye without his receiving auditory or vibrational cues to its changes. It can be directly and very conveniently driven with the output of an oscillator (or, with the addition of a multiplier, by the analog output of a laboratory computer): and despite its relatively long time constant, the twisted-nematic cell can pass from one density to another with at least the speed of a neutral density wedge mounted on a stepping motor.

The twisted-nematic cell will be especially appropriate in experiments where stimulus intensity is to be titrated according to a staircase procedure (Cornsweet, 1962). Figure 4 shows measurements of the Pulfrich effect made firstly by the conventional method of titrating interocular delay while holding attenuation constant (●) and secondly by titrating the attenuation of the left-eye signal while holding constant the interocular delay (○). The stimuli were bright, green,

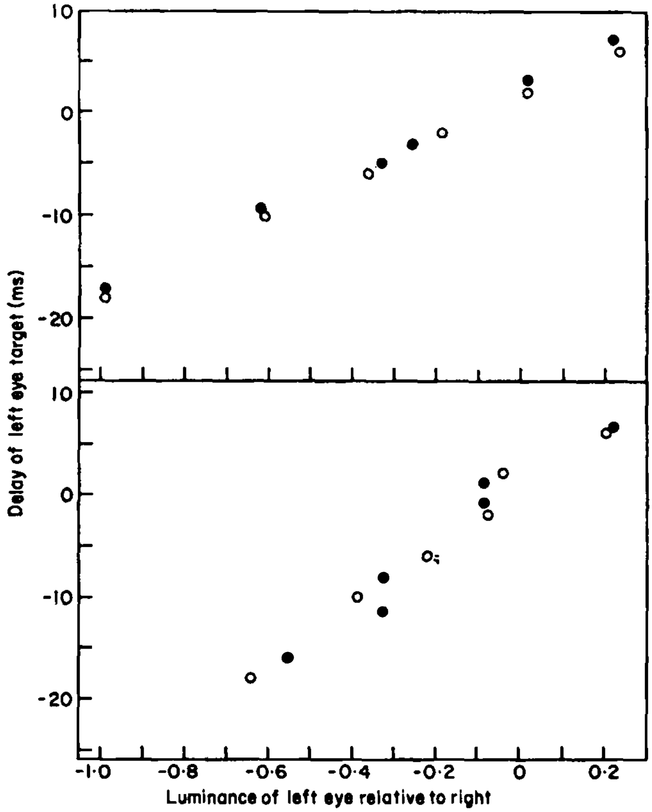

FIGURE 4. Measurements of the Pulfrich effect. Upper panel: stimulus luminance = 3·3 log cd/m². Lower panel: stimulus luminance = 1·3 log cd/m². Titration of interocular delay (●); titration of attenuation (○).

vertical bars displayed on an oscilloscope in a manner similar to that described by Morgan and Thompson (1975). An artificial pupil was mounted in front of each eye and a twisted-nematic cell was placed between the left-hand pupil and the display. Under computer control the two methods of titration were used in alternate blocks of 60 trials; they show good agreement.

We do not, however, recommend the twisted-nematic cell for use with white light, since attenuation does not proceed quite concomitantly for all wavelengths. Nor do we recommend such a cell where a large aperture is required, since the voltage needed to achieve a given attenuation will almost certainly vary across the cell's surface, owing to slight variations in the separation of the glass plates. A third disadvantage is that the function relating voltage to transmission [Fig. 3(b)] may show small lateral shifts along the abscissa from day to day. However, in our measurements of the Pulfrich effect (Fig. 4) we found that the cell remained stable for the course of experimental sessions lasting several hours. Where long-term stability is required, it can be obtained with a feed-back circuit. Using the rudimentary feed-back circuit of Figure 5(a) we have been able to stabilize transmission to within 0·01 log units. A secondary advantage of this circuit is that transmission changes less rapidly with changes in the controlling voltage [Fig. 5(b)].

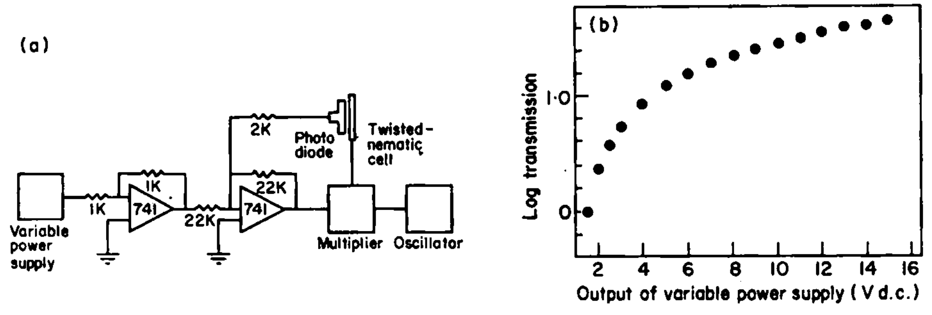

FIGURE 5. (a) A simple feed-back circuit used to control a twisted-nematic cell. (b) Transmission as a function of the output of the variable power supply.

We have also found it convenient to stabilize a twisted-nematic cell by feed-back from digital computer: the transmission of the cell was monitored with a silicon photodiode and this signal was fed to the computer via an analog-to-digital converter; the computer program adjusted the d.c. voltage applied to a multiplier (and thus the a.c. voltage applied to the cell) to amintain a constant value at the analog-to-digital converter. The optical apparatus was some distance from the computer and, to render the feedback circuit insensitive to high-frequency noise arising in the connecting cables, adjustments were made on the basis of 10-s samples of the input. By this means we secured long-term stability to within 0·02 log units, the limitation proving to be the resolution of our analog-to-digital and digital-to-analog converters. We judge that a twisted-nematic cell would prove very convenient as a filter where a computer is already being used to conduct an experiment.

Figure 6 demonstrates how a fast shutter can be constructed from twisted-nematic cells. Two cells are placed between three polarizers in a double sandwich.

The principle is to open the shutter by energizing one cell and to close it by energizing the second: thus a short time constant will be obtained at both onset and offset. When no field is applied to either cell the shutter is opaque, owing to the rotation of the plane of polarization at Cell 1. Application of a voltage to Cell 1 makes the unit transparent. If this voltage is maintained and a further field is applied across Cell 2 the unit again becomes opaque. To return to the initial state while maintaining extinction, the field must first be removed from Cell 1 and then, after several hundred ms, from Cell 2. Thus a limitation of the unit is that successive exposures must be separated by relatively long intervals. A second limitation is that the extinction of the closed shutter has different values according to whether the two parts of the unit are individually closed. We do not therefore recommend the twisted-nematic shutter for general purposes; but when absolute silence and single brief exposures are required it may offer a cheap and satisfactory solution.

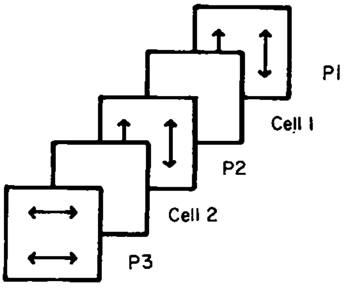

FIGURE 6. A fast shutter constructed from two twisted-nematic cells.

Colour effects

By introducing a retardation plate (e.g., a piece of Cellophane) into the twisted-nematic assembly, a display of variable colour can be produced. We do not review electronically-variable colour filters here but refer the reader to Tobias (1975), Williams (1975) and Tarry (1975) where a number of such devices are discussed.

General remarks on the use of liquid-crystal cells

In preparation and mounting, cells should not be subjected to any mechanical strain, since even a light pressure may critically change the separation of the plates. Thus it is unwise to hold a cell in a retort clamp. It is often convenient to glue polaroid sheets permanently to a twisted-nematic cell, but care must be taken that the adhesive does not introduce stresses as it hardens.

We have found it important to check that a good and unvarying contact is made to the transparent electrodes on the glass plates of the cell. Crocodile clips prove unsatisfactory and we suggest attaching permanent leads to the electrode surface by means of a conductive epoxy*. The plated glass should not be handled with the fingers.

Many cells will work if a d.c. field is applied; but, owing to ion depletion and electrolysis, the material will soon deteriorate. Before a connection is made to a cell, it is always important to check that the electrical signal is what it is thought to be.

There is said to be evidence that nematic materials rapidly penetrate the skin. No health hazard is known, but the materials are new and skin contact is best avoided.

Conclusions

Novelty for its own sake has no virtue and our survey leads us to prefer a conventional shutter where it is adequate. The criteria for judging a shutter are speed, extinction, quietness, reliability, aperture-size, compactness, cost and the simplicity of the associated electronics. Liquid-crystal devices will recommend themselves when silence or compactness are critical. They are cheap and reasonably fast. The phase-change device will be especially useful where the transition is from a diffuse adapting field to a patterned stimulus field. The twisted-nematic cell will be primarily of advantage as a cheap and compact, electronically-variably filter, although we have suggested how a fast shutter could be constructed from two such cells.

What is very probable is that there will be further rapid improvements in liquid-crystal devices. Liquid crystals are now widely used to provide the displays in electronic calculators and in digital wrist-watches; and commercial pressure for wrist-watch displays that register seconds should lead to improvements in switching-speed and to reductions in cost, while the development of an electro-optic camera-shutter should lead to improvements in extinction.

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* A suitable plastic adhesive with low electrical resistance is Eccobond 56C supplied by Emerson and Cuming, 1 South Park Road, Scunthorpe, Lincs, DN17 2BY, U.K., or Canton, Mass., USA.

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