

# Liquid crystal lens review

C. W. Fowler\* and E. S. Pateras

Department of Vision Sciences, Aston University, Aston Triangle, Birmingham B4 7ET, UK

(Received 18 September 1989, in revised form 10 November 1989)

Liquid crystal lenses are possibly the spectacle lenses of the future for presbyopic corrections. They present a variable refractive index which can be used to produce the necessary addition needed for presbyopia. The variability of the refractive index is due to the fact that these materials are optically anisotropic. This effect is obtained by the application of an electric or magnetic field through the liquid crystal layer. A review of the literature relating to the evolution, the preparation and the operation of these lenses is given. A discussion is also included of the practical problems and drawbacks, which at present limit their use, and possible solutions.

Liquid crystals are organic compounds which exhibit mesomorphic behaviour. The term mesomorphic signifies a state, which lies between the crystalline solid state, where there is no mobility of individual molecules, and the isotropic phase (amorphous liquid), where mobility exists, providing in this way molecular disorder. These organic compounds can also be found in the solid and isotropic state. Their transition from one state to another can be attained either by thermal process (thermotropic mesomorphism) or by the influence of solvents (lyotropic mesomorphism).

According to Gray<sup>1</sup>, liquid crystals exhibiting thermotropic mesomorphism are classified broadly into three types depending on their molecular structure: the nematic, the smectic and the cholesteric. The molecular ordering in a nematic liquid crystal is such that there is no regular arrangement between neighbouring molecules. Smectic liquid crystals have stratified structures but a variety of molecular arrangements is possible in each stratification and, depending on their arrangement, they are divided into smectic liquid crystals of the A, B and C type. Cholesteric liquid crystals are characterized by their helical aggregates of molecules.

Liquid crystals were discovered by Reinitzer in 1888 and later by Lehmann in 1890<sup>1</sup>. More information about the history of liquid crystals is given by Kelker<sup>2</sup>, who placed the first report about them in 1837 in a novel by Edgar Allan Poe. Their electro-optical and magneto-optical properties make liquid crystals useful for different kinds of commercial applications. For example, they are used to indicate skin temperature<sup>3</sup>, in electronic displays like calculators, watches, clocks, and in many other devices<sup>4</sup>.

Besides the above applications, a variety of devices have been recently reported to incorporate a lens-cell filled with liquid crystals of variable refractive index. Such a lens incorporates liquid crystals, which obtain the

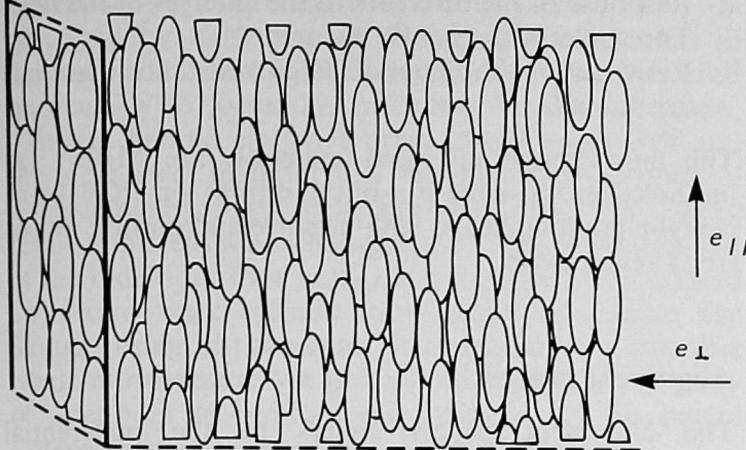
nematic structure; to achieve this variation in the refractive index of the material a voltage must be applied. By changing the voltage applied, changes in the optical properties of the material will be induced, which produce a change in the refractive index of the material.

Today's varifocal spectacle lenses, which have met with commercial success over the years, are the progressive addition lenses. The performance of these lenses relies on a front surface of complex aspheric shape to provide a smooth transition from distance to near portion with constant power. Looking at their optical characteristics, the effective field of view through the transition zone clearly consists of a very narrow corridor, whereas outside the corridor a substantial amount of astigmatism and distortion is present. A liquid crystal lens has a totally different approach to providing intermediate vision. For a presbyopic patient the intermediate vision is not limited to a narrow corridor as in the progressive addition lenses, but each of the transition powers (steps of power between the distance and near vision) will be able to occupy the whole aperture of the lens. The same is valid for the distance and near vision powers. With such a lens a presbyopic patient will have the greatest possible field of view for the distance, intermediate and near vision, and the lens would be free of astigmatism and distortion compared with the aspheric design of the progressive addition lenses. Such an advantage would probably eliminate even the small percentage of presbyopic patients who failed to adapt to the progressive addition lenses<sup>5</sup>.

## Birefringence

To understand the mechanism of the liquid crystal lens, some of the properties of the nematic structure must be detailed. As mentioned above, the nematic phase is of particular importance in producing a liquid crystal lens with a variable refractive index. The molecules of a nematic liquid crystal material generally possess a rod-shaped or disc-shaped configuration. The material which is used in such a lens consists of rod-shaped organic

\* FBCO



**Figure 1** Schematic diagram of the structure that the molecules of a nematic material assume. It can be seen that there is no regular arrangement between them; only their long axes are in a parallel alignment

molecules. *Figure 1* shows part of the molecular structure of a nematic material. It can be seen that there is no regular arrangement between neighbouring molecules. There is, however, an average direction of the long axes of the molecules in a certain region. This direction is designated as the director of the region, which is responsible for the phenomenon of birefringence. The type of material exhibiting this phenomenon is designated optically anisotropic.

According to geometrical ray optics, birefringence refers to the splitting of a light ray into two components when it enters solid uniaxial crystals like calcite and tourmaline. These two components, which have orthogonal polarizations, are the ordinary ray and the extraordinary ray. The refractive index of the ordinary ray is independent of the orientation of the initial beam entering the material. By contrast, the refractive index of the extraordinary ray depends on the angle between the initial beam and the orientation of the optical axis of the materials, which in liquid crystals is the director of the region. Hence, when the material is tilted, while the orientation of the initial beam is kept constant, a variation in the refractive index of the extraordinary ray is induced. In liquid crystals, the tilting is obtained by application of an electric or magnetic field. The field controls and changes the orientation of the directors in each region, so that the index presented by the liquid crystals varies between the ordinary index ( $n_o$ ) and the extraordinary index ( $n_e$ ).

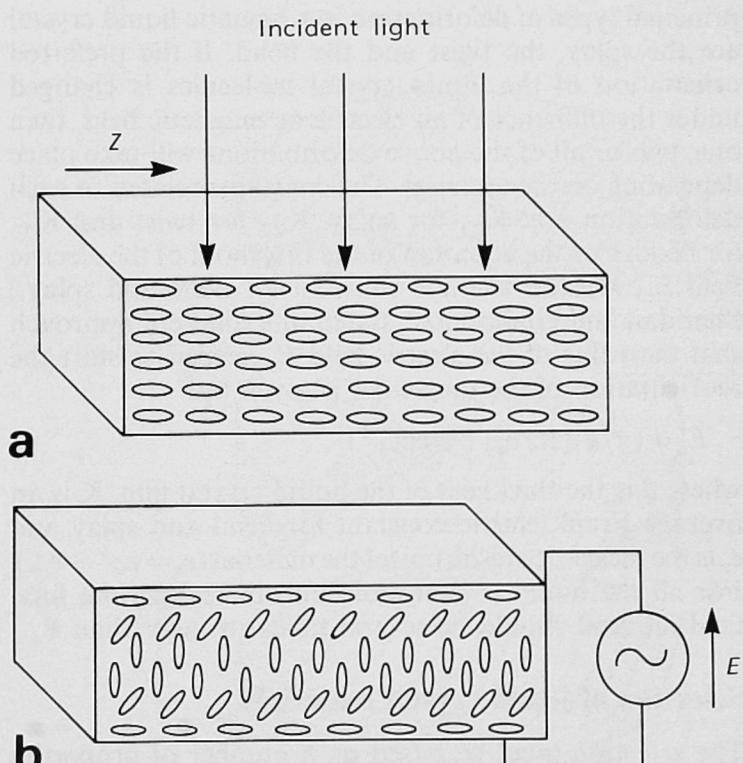
### Liquid crystal lens operation

A liquid crystal lens utilizes the effect of birefringence to present a variable focal length, but it should be mentioned that the beams entering the lens must be linearly polarized. The variation occurs as a result of the applied field parallel to the propagation of the entering beam and causes the molecules to rotate.

According to Gray<sup>1</sup> and Saeva<sup>4</sup>, liquid crystals exhibit an anisotropy in their dielectric and diamagnetic constant (The dielectric constant, known also as relative permittivity, is the ratio of the permittivity of a substance to that of a vacuum ( $\epsilon = \epsilon_s / \epsilon_0$ ). The diamagnetic constant, known also as relative permeability, is the ratio of the permeability of a medium to that of free space ( $\mu = \mu_m / \mu_0$ .). Liquid crystal molecules of the nematic type can be characterized as dipoles, having  $\epsilon \perp \neq \epsilon \parallel$  or  $\mu \perp \neq \mu \parallel$ ,

where  $\epsilon \parallel$  and  $\mu \parallel$  are the dielectric and diamagnetic susceptibilities parallel to the axis of symmetry when the maximum molecular alignment has been attained, which means they are parallel to the long axes of the molecules. Conversely,  $\epsilon \perp$  and  $\mu \perp$  are the dielectric and the diamagnetic susceptibilities perpendicular to the axis of symmetry, that is perpendicular to the long axis of the molecules. Owing to this anisotropy, when an electric or magnetic field is applied, the molecules will tend to align themselves such that the dielectric or diamagnetic susceptibility of the largest value will align with the direction of the electric or magnetic field. The nematic liquid crystals, according to the value of their dielectric or diamagnetic susceptibilities, exhibit either a positive or a negative dielectric or diamagnetic anisotropy. If  $\epsilon \parallel > \epsilon \perp$  or  $\mu \parallel > \mu \perp$ , then the nematic material is characterized as positive and the directors tend to align parallel with the field applied, while when  $\epsilon \parallel < \epsilon \perp$  or  $\mu \parallel < \mu \perp$  then it is characterized as negative and the directors are aligned perpendicular to the field.

In the case where a liquid crystal with positive dielectric anisotropy is placed in a cell consisting of two transparent flat glass plates and a spacer, which provides the space where the liquid crystal will be placed, then the molecules' long axes will orientate in a direction  $Z$  parallel to the plates. This parallel alignment with the plates is attained after a suitable preparation (alignment process), which is related to the inner parts of the plates. *Figure 2(a)* shows a configuration like the one mentioned above with the molecules in a parallel direction with the plates. The optical axis of the liquid crystals, which is designated by the orientation of the molecules and in this case is presented by the direction  $Z$ , is related to the ordinary ray. The incident beam is perpendicular to the plates and to the orientation of the optical axis. If the incident beam is also polarized in the direction  $Z$ , then the refractive index presented by the device will be the extraordinary index ( $n_e$ ).



**Figure 2** (a) Liquid crystal film placed in a cell and (b) with a field  $E$  applied. The direction of the optic axis of the liquid crystal is presented by  $Z$ . The molecules tend to orientate their long axes according to the field's direction

After covering the inside surface of the plates with transparent electrodes, an electric field is applied by means of voltage source. The field causes the molecules to rotate and acquire an orientation parallel to the field  $E$ , as illustrated in *Figure 2(b)*. Providing there is sufficient intensity of the field  $E$ , the refractive index will change to the ordinary index ( $n_o$ ). By removing the field  $E$ , the molecules will reorientate and acquire their initial orientation parallel to the plates. Consequently the index will revert to the extraordinary index ( $n_e$ ).

If a liquid crystal material possessing a negative dielectric anisotropy, is now placed with the same configuration as in *Figure 2(b)* then, with suitable preparation, the long axes of the molecules will obtain a direction perpendicular to the plates. If a light beam is incident perpendicular to the plates, polarized also in a direction  $Z$ , then the opposite events take place when the field is on and when it is off. Consequently, the ordinary index ( $n_o$ ) is present when the field is off and the extraordinary index ( $n_e$ ) when the field is on.

For plane-polarized light incident perpendicular to the cell plates, the anisotropy presented by the material is given by the Kerr equation<sup>6</sup>:

$$\Delta n = n_e - n_o = B\lambda E^2$$

where  $\lambda$  corresponds to the wavelength of the incident light,  $E$  is the electric field applied and  $B$  is the Kerr constant.

It is important to mention that to induce a reorientation of the molecules, the field should have sufficient power. It is understood that the change in the orientation will appear only when the field reaches the threshold voltage for inducing such a change,  $V_{th}$ . This is given by Labrunie and Roberts<sup>7</sup> as:

$$V_{th} = 2\pi(\pi K_{33}/e_a)^{1/2}$$

where  $K_{33}$  is the elastic constant of bend curvature in Franks notation and  $e_a$  is the dielectric anisotropy of the material ( $e_a = e_{\parallel} - e_{\perp}$ ). (According to Frank<sup>8</sup>, the principal types of deformation in a nematic liquid crystal are the splay, the twist and the bend. If the preferred orientation of the liquid crystal molecules is changed under the influence of an electric or magnetic field, then one, two or all of the above deformations will take place depending on the material. The constants related to each deformation are:  $K_{11}$  for splay,  $K_{22}$  for twist and  $K_{33}$  for bend. For the equation of the threshold of the electric field  $E_c$ ,  $K$  is an average constant for bend and splay.) Sheridan and Giallorenzi<sup>9</sup> stated in a different approach that the value of the electric field  $E_c$  needed to start the reorientation of the molecules is given by:

$$E_c = (\pi/d)(K/e_a) (V \text{ cm}^{-1})$$

where  $d$  is the thickness of the liquid crystal film,  $K$  is an average Frank elastic constant for bend and splay and  $e_a$  is the dielectric anisotropy of the material ( $e_a = e_{\parallel} - e_{\perp}$ ). For all the liquid crystal molecules to realign, the final field induced should be several times stronger than  $E_c$ .

### Selection of liquid crystal materials

The selection must be based on a number of properties that these materials exhibit and are described below.

1. Temperature range over which the material obtains the nematic structure. Room-temperature nematic liquid crystals are preferable.

2. Response of the directors to the changes of the field.
3. Threshold of the field's strength.
4. Resistivity of the material. High resistance materials are suitable.

The most commonly used materials are MBBA (*p*-methoxybenzylidene-*p*-n-butylaniline) or PCB (*p*-n-pentyl-*p*-cyanobiphenyl) with negative and positive anisotropy respectively.

### Alignment process

The alignment process refers to the preferential orientation of the molecules, so that the directors of all the regions of the liquid crystal layer will be aligned in the same direction parallel or perpendicular to the supporting plates of the cell. This process is divided into the initial alignment, which the molecules have in the quiescent state, and the induced alignment, which results from the application of the electric field.

Owing to the relationship between the molecular alignment and the optical properties of liquid crystals, the alignment has to be perfect and uniform. Many techniques have been reported to produce the initial alignment. According to whether the material has positive or negative anisotropy, the initial alignment must be parallel or perpendicular to the supporting plates respectively. The simplest, which induces parallel alignment, has been reported by Chatelain<sup>10</sup>. He achieved uniform alignment by rubbing the inner surfaces of the plates with a piece of cotton or cloth. The success of Chatelain's method was explained by Berreman<sup>11</sup> to be due to groove formation along the inner surfaces of the plates.

Janning<sup>12</sup> demonstrated another method when he deposited by evaporation at an angle a thin film of silicon monoxide (SiO) on the inner surfaces of the plates of the cell. This technique gives better results than Chatelain's method because the influence on the molecules of the liquid crystals lasts for a longer period. Depending on the angle of evaporation, the orientation induced is parallel or perpendicular. Janning's method is the most commonly used to date. Suitable additive materials, such as the long chain alkyl pyridinium or quarternary ammonium salts and surface-active agents such as lecithin<sup>13</sup> and siloxanes<sup>14</sup>, can play a significant role in the alignment. Perpendicular orientation is obtained by treating the inner surfaces again with sulphuric acid and then rinsing with distilled water<sup>4</sup>.

### Liquid crystal lens evolution

In 1933, Skaupy introduced an apparatus for reflecting light rays<sup>15</sup>. The optical device produced varying deflections of light rays and was intended to be used in picture telegraphy or any other related use. The cell incorporated one or more prisms of a double-refractive substance, in this case nitrobenzene. The change of the ray paths was induced by an application of an electric field.

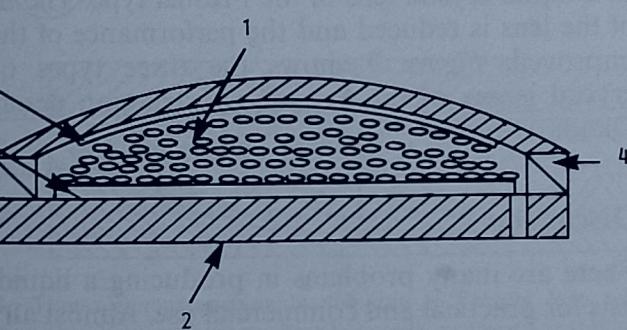
A UK patent was granted in 1959 to a Swiss Organization (No 808981), which was related to an optical system used to amplify the intensity of light of an optically-projected image using a multilayer liquid crystal cell<sup>16</sup>. One of these layers was a substance which could be influenced by an electric-Kerr effect. The electrodes used were made of platinum.

Another type of electro-optic adjustable lens was described by Kosanke and Kulcke<sup>17</sup>. It was used to control and direct electromagnetic radiation and particularly to focus this radiation on selected points. The lens had an electrode array of a Fresnel type and the Kerr-effect material was this time a solid plate of potassium dihydrogen phosphate ( $\text{KH}_2\text{PO}_4$ ). The desired result of this lens was a change in the status of polarization of the radiation. Two years later, Lotspeich<sup>18</sup> produced an electro-optic variable focal length lens, again like Skaupy using nitrobenzene. It consisted of a chamber where nitrobenzene was placed and a quatropolar array

to produce the variation. In his patent

gives in detail the related theory.

In 1972, Haas *et al.* used an electro-optic system to an imaging system<sup>19</sup>. They suggested different materials as supporting walls, such as glass, polyethylene or polyvinylchloride and aluminium, silver oxide for electrical conductors. As for the liquid substance, a list of materials is included in the patent, BA. The thickness of the layer was about  $250 \mu\text{m}$ . Sprokel<sup>20</sup> explained in his patent the use of birefringence in electro-optic information systems. He suggested that thickness of the layer should not exceed  $20 \mu\text{m}$ . The two patents granted to him in 1977<sup>21,22</sup> were related to electro-optic devices using homeotropically aligned nematic material. Sprokel gave information on how liquid crystal cells operate and suggested that K® mixture should be used. Bricot *et al.*<sup>23</sup> produced a crystal lens having a variable refractive index changes in the field applied. Figure 3 illustrates a cell arrangement which was used in an optical system. According to them, the nematic liquid should change dielectric anisotropy sign with frequency of the field. These materials have anisotropy, which is positive at any field frequency  $f$  above reference frequency  $f_r$ . Above  $f_r$  their anisotropy is negative, e.g.  $f_r = 10 \text{ kHz}$  at  $T = 25^\circ\text{C}$ . The change in the refractive index is about  $\Delta n = 0.2$  for  $10 \text{ kHz}$ . Their response time is about 5 ms. Fray used a different approach. They produced an electrically switchable lens, to be more specific, a lens with a gradient index through its aperture. The gradient index was obtained by changing the polarity in one of the electrodes used. The positive nematic material assumes the structure shown in Figure 4 when the field is on, thereby producing a gradient index portion. Berreman<sup>25,26</sup> also introduced a liquid crystal cell to be used in cameras, telescopes, binoculars, projectors and glasses. This is probably the first time that such a lens was proposed to be used for spectacles. The lens shown in Figure 5 is the one used by Berreman. It consists of a



Liquid crystal lens-cell according to Bricot's invention. (1) Polarizer film, (2) lens-cell, (3) electrodes to induce the field and (4) source. After reference 23

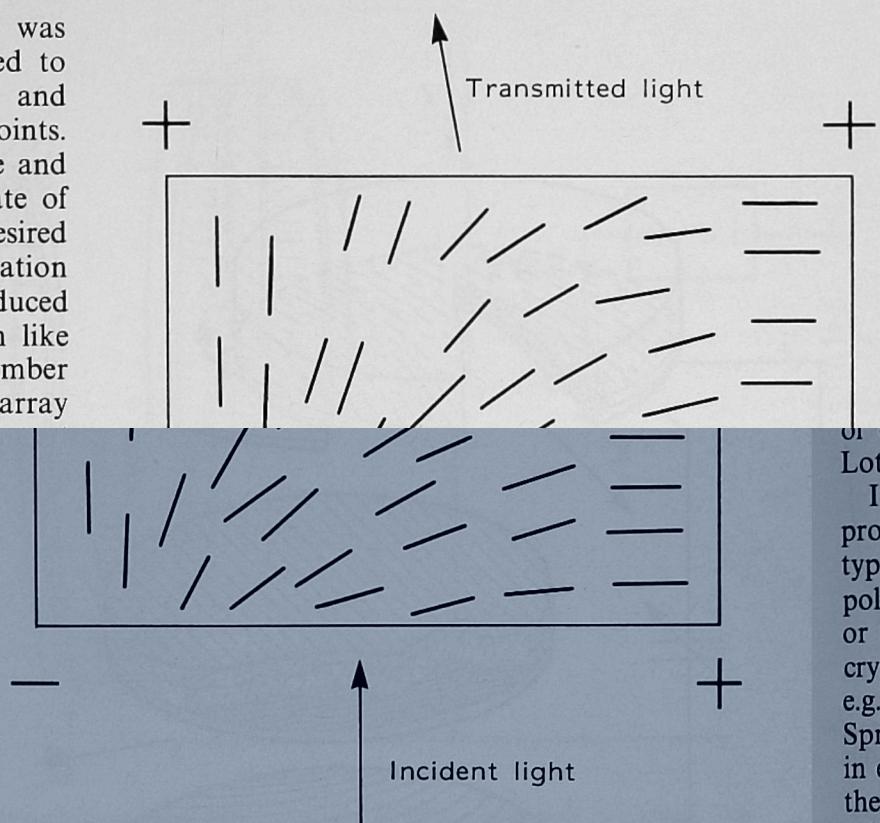


Figure 4 Molecular arrangement when the field is on according to Fray's invention. It can be seen that the change in the polarity of one of the electrodes produces a gradient index portion on the lens. After reference 24

polarizer (1) orientated in a direction X, which also is the direction imposed on the directors of the nematic material. Layers (2) are used to induce initial alignment of the molecules. Electrodes (3) are used for the application of the field, while (4) is the source producing the field and walls (5) support the cell. Figure 6 is another type

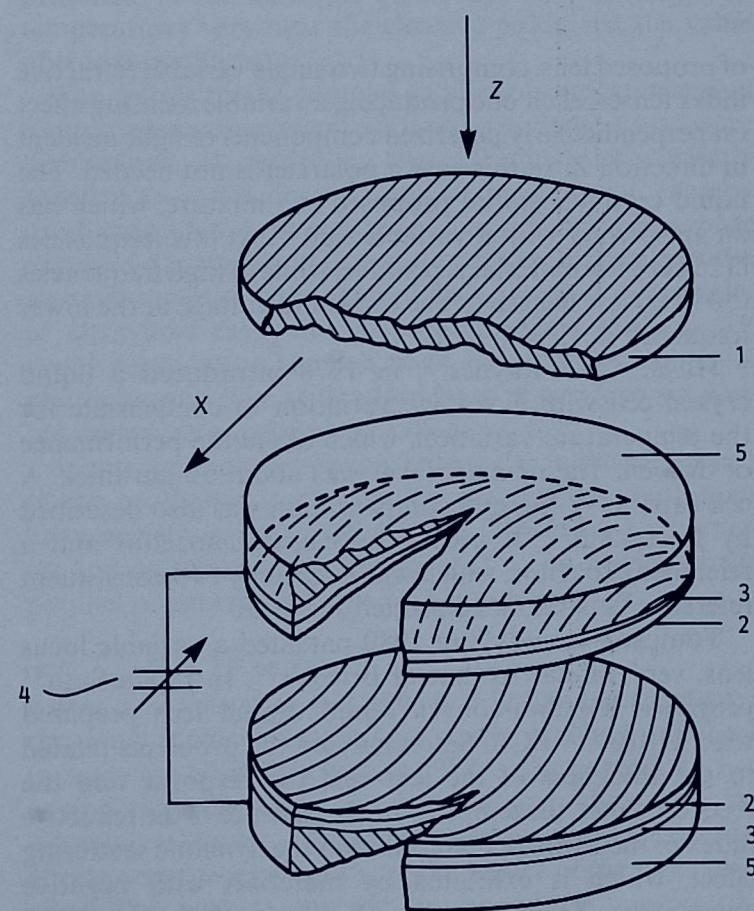
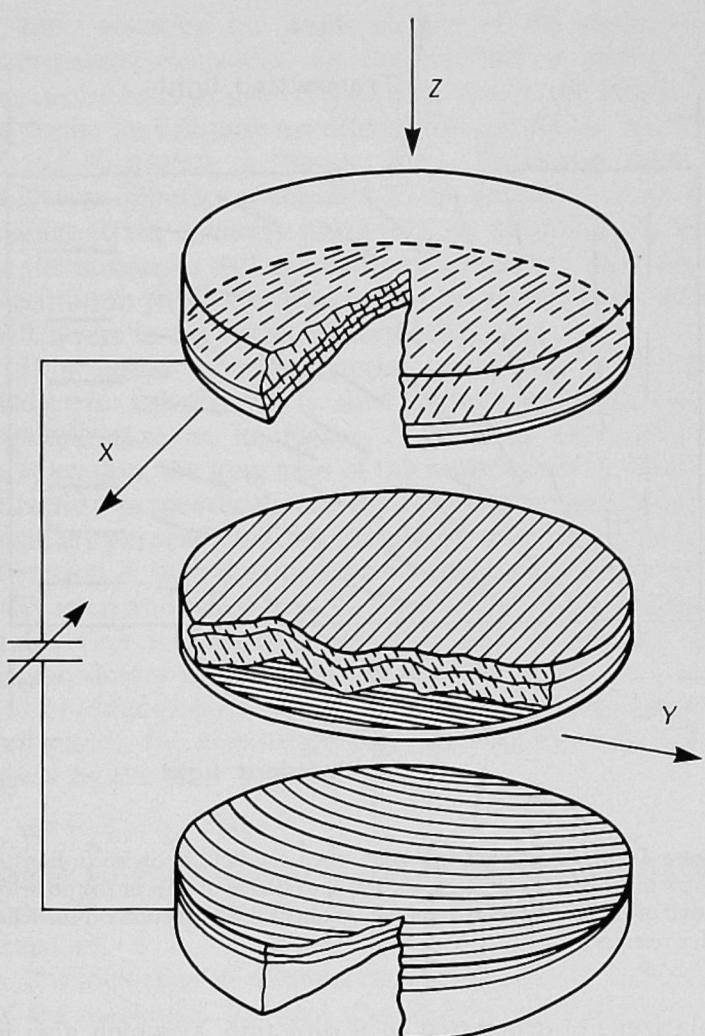


Figure 5 Berreman's liquid crystal lens configuration. After reference 25

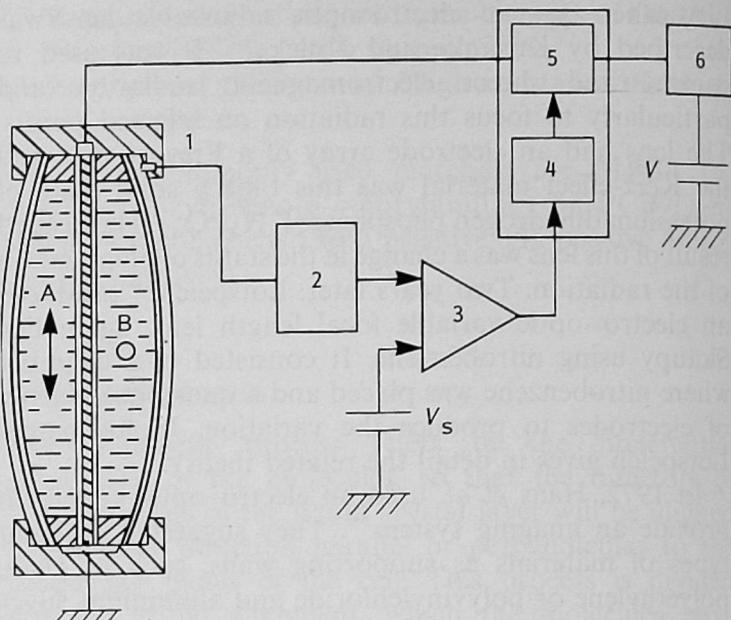


**Figure 6** Berreman's second type of liquid crystal lens. Such a lens does not need a polarizer to operate, because the lens produces a variable focusing effect on incident light independent of its polarization. This is due to the fact that the lens consists of two single variable focus lenses with their directors in perpendicular orientation to each other. After reference 25

of proposed lens, comprising two single variable refractive index lenses, each one producing a variable focusing effect on perpendicularly polarized components of light incident in direction Z. In this case a polarizer is not needed. The liquid crystal material proposed is a mixture, which has an anisotropy with a variable sign<sup>27</sup>. At low frequencies (125 Hz), the material is positive, while at high frequencies (50 kHz) it is negative. The threshold voltage at the lower frequency is  $V_{th} = 1.95$  V.

Hilsum and Raynes<sup>28</sup>, in 1978 introduced a liquid crystal cell with a voltage variation to compensate for the temperature variation, which alters the performance of the cell. The nematic layer was about 12  $\mu\text{m}$  thick. A cell capable of thermal compensation was also described by Portmann<sup>29</sup>. It used a measuring capacitor and a reference capacitor, which was formed by two constituent reference capacitors connected in series.

Tompson-Brandt<sup>30</sup> in 1980 patented a variable focus lens, very similar to that of Bricot's<sup>30</sup>. In Japan Sato<sup>31</sup> proposed a plano-convex liquid crystal lens prepared with MBBA or PCB. Sato analysed the problems related to the thickness of the lens-cell, the response and the recovery times, the temperature dependence of the refractive index of the nematic materials and the dynamic scattering effect, which is exhibited by materials with negative anisotropy. To reduce the thickness of the lens and consequently the thickness of the liquid crystal layer, Sato *et al.*<sup>32</sup> proposed the use of a convex Fresnel lens which



**Figure 7** Liquid crystal lens system proposed by Okada *et al.*<sup>33</sup>, with means of temperature compensation for the temperature dependence of the refractive index. (1) Temperature sensor, (2) temperature detecting and processing unit, (3) comparator, (4) correction unit, (5) variable voltage circuit and (6) DC/AC converter. After reference 33

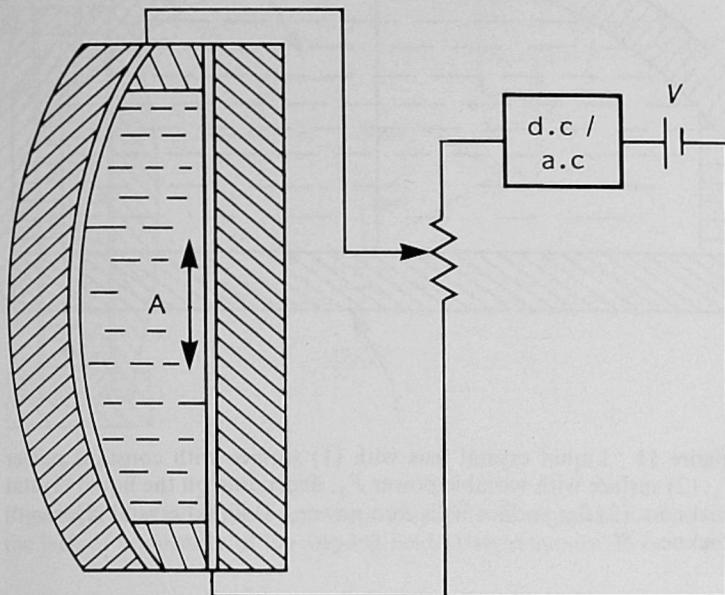
also improves the response and recovery times of the nematic material. The lens was specifically made for spectacles. By incorporating a Fresnel lens, the transparency of the lens increases up to 80% or more as a polarizer is not needed in the configuration they proposed. They used a double-layered structure of two identical Fresnel cells with mutually orthogonal optical axes and the material had a positive anisotropy and a thickness of 100–250  $\mu\text{m}$ .

To date the most advanced liquid crystal lens for spectacles has been described by Okada *et al.* He was granted two patents in 1986 and one in 1987. In the first patent<sup>33</sup> he introduced a liquid crystal lens with variable refractive index according to a variable voltage source applied and means for detecting and compensating for any change in the refractive index, which is attributable to any temperature change. In this way he intended to keep the refractive index exhibited by the liquid crystal lens independent of any temperature change. Figure 7 shows the optical system proposed. In the second patent<sup>34</sup> at least part of the cell is formed of a photochromic material. The photochromic material acts as a barrier to harmful radiation and prevents degradation of the liquid crystal material. To achieve better results a combination of photochromic material with a film of an acrylic resin combined with neodymium (Nd) can be used. Figure 8(a) and (b) shows two of the proposed configurations of the optical system. The third patent, in 1987<sup>35</sup>, is related to a liquid crystal lens of the Fresnel type. The thickness of the lens is reduced and the performance of the lens is improved. Figure 9 shows the three types of liquid crystal lenses of the Fresnel construction described by Okada *et al.*<sup>35</sup>

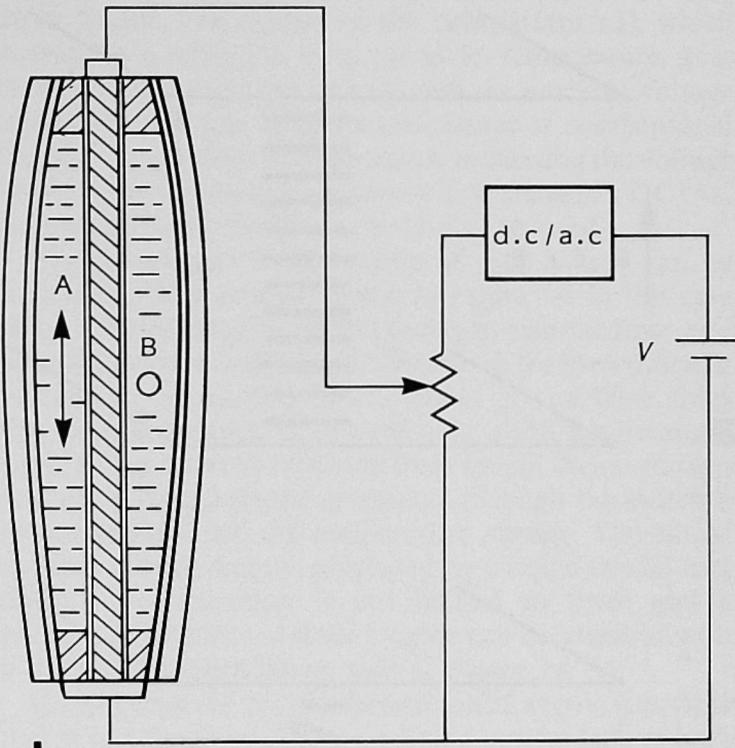
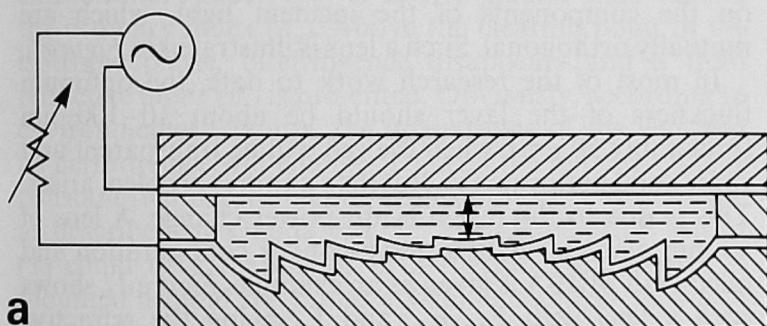
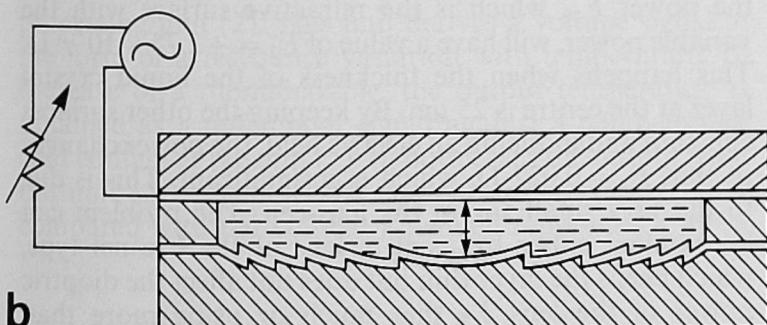
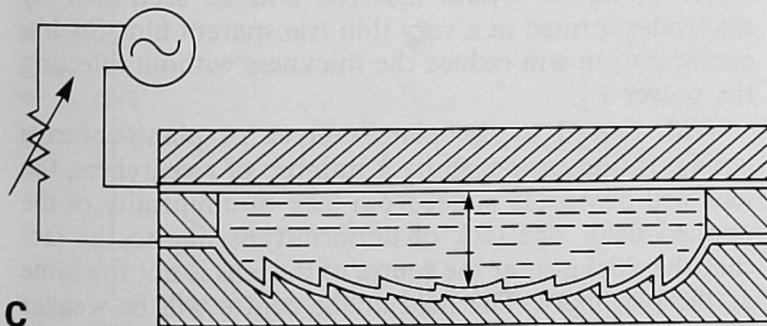
## Discussion

There are many problems in producing a liquid crystal lens for practical and commercial use. Almost all of these problems are related to the material selected.

To prepare liquid crystal lens-cells of high quality and performance, the material has to have a large birefringence,

**a**

**Figure 8** (a) Plano-convex liquid crystal lens with surface composed of photochromic glass with a thin film of acrylic resin with Nd added. The orientation of the molecules is given by the direction A. After reference 34. (b) Biconvex liquid crystal lens with A being the orientation of the molecules for the front part of the biconvex lens and B being the orientation of the molecules for the back part of the lens. A and B are perpendicular to each other. After reference 33

**b****a****b**

**Figure 9** Three lens arrangements showing a Fresnel lens with (a) negative, (b) plano, and (c) positive lens cells, proposed by Okada *et al.* These are typical examples of Fresnel lenses, which are used to reduce the thickness of the liquid crystal layer without affecting the total focusing power of the lens. After reference 35

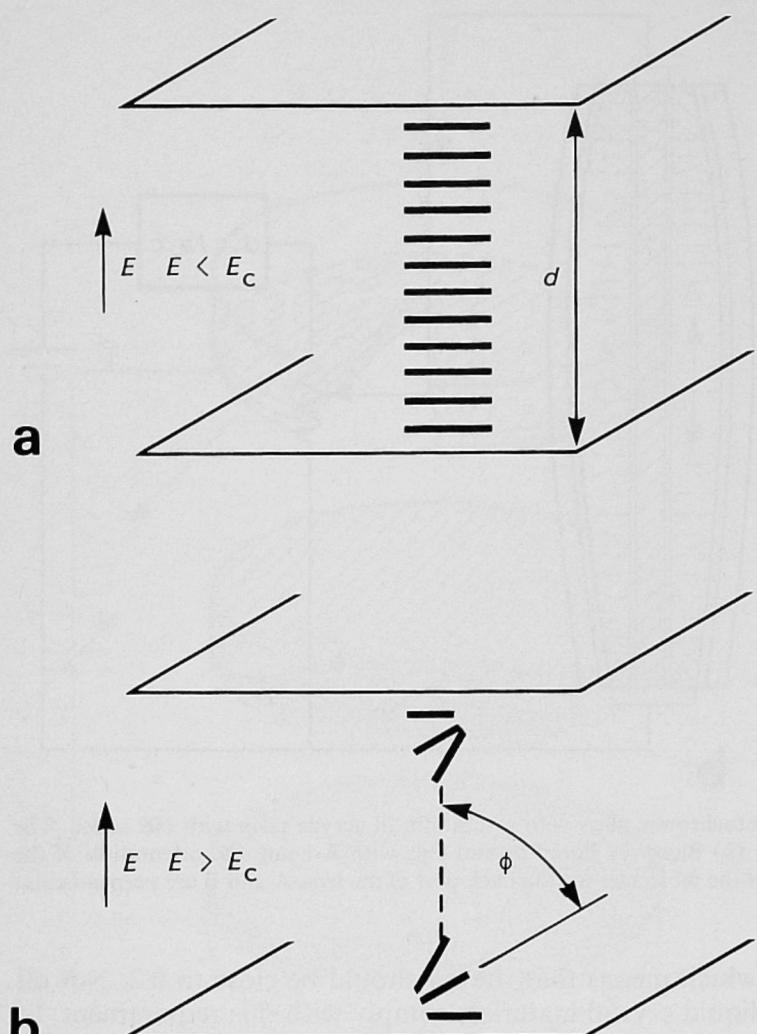
which means that the  $\Delta n$  should be close to 0.2. Not all liquid crystal materials comply with this requirement. In practice there are a number of materials which have a  $\Delta n$  close to this value, but there is a limitation to their usage, depending on their nematic temperature range. These materials must have transition temperatures between  $-10^{\circ}\text{C}$  (from solid to the nematic phase) and  $+60^{\circ}\text{C}$  (from nematic to the isotropic phase). Birefringence is also exhibited in the isotropic phase by these materials in temperatures very near the clearing point, but the value of it is insignificant.

The purity of the samples is also of importance and for this reason these materials have to undergo six or more distillations. In addition, the cell must be perfectly shielded to avoid degradation of the material, thereby producing a lens-cell with properties different from those expected. Degradation can also occur by exposure of the nematic material to a light of high intensity (especially to ultraviolet rays) due to photochemical changes. To avoid degradation the cell must be protected by using photochromic glass with a thin layer of acrylic resin with Nd added, as suggested by Okada *et al.*<sup>34</sup>

It was mentioned previously that the initial alignment of the molecules is parallel. In practice, the molecules have an average parallel alignment. This is due to thermal motion as reported by DeGennes<sup>36</sup>. The degree of the parallel alignment is given by Chen *et al.*<sup>37</sup> as:

$$S = 1/2(3 \cos\theta - 1)$$

where  $S$  is the order parameter,  $\theta$  is the angle between the long molecular axis and some external reference (usually the boundary surface). When the angle  $\theta$ , known as the tilt bias angle, reaches certain values and the material is under certain conditions, light scattering effects occur, degrading the performance of the lens. Also, when the field is on, due to boundary tension, the molecules near the boundary surface do not follow the new orientation induced by the field, creating a lack of

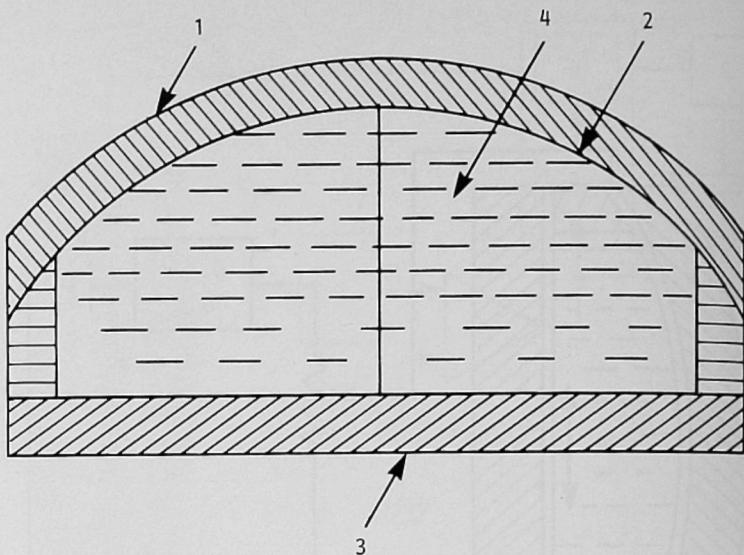


**Figure 10** Schematic diagram of the liquid crystal molecules of a positive nematic material when the field  $E$  is off (a) and on (b). The molecules near the boundaries clearly do not follow the reorientation process to the same degree as those in the middle. The thickness of the layer is  $d$

uniformity through the bulk of the layer. Figures 10(a) and (b) show the reaction of the molecules during the reorientation process. Sometimes, when the field is on and the material has a negative anisotropy, the dynamic scattering effect (DSE) takes place. This phenomenon was first discussed by Heilmeier *et al.*<sup>38</sup>, and it is usually followed by turbidity through the liquid crystal material. Above a certain frequency threshold, which depends on the material, this effect ceases.

Two other properties of liquid crystal lenses, which must be taken into account, are the response and the recovery times of the material. In practice, this means the ease with which the molecules change from the quiescent state to the induced reorientation state. These two properties are related to the thickness of the layer. As the thickness of the film becomes larger, the response and the recovery time lengthen. These can be improved by adopting the structure of a Fresnel lens as suggested by Sato *et al.*<sup>32</sup>.

The thickness of the layer is perhaps the most important factor in determining the usefulness of such a lens, as it has been found to influence the transmission of the lens. The transmission of light entering the lens is expected to decrease as the absorption of the nematic material increases and scattering effects take place. As mentioned previously, by increasing the thickness of the layer, the molecules at the centre of the lens will have different orientations to those near the boundary surfaces when the field is on. In the case of a plano-convex cell with



**Figure 11** Liquid crystal lens with (1) surface with constant power  $F_1$ , (2) surface with variable power  $F_2$ , depending on the liquid crystal thickness, (3) flat surface with zero power, (4) liquid crystal layer with thickness  $S$

MBBA, the centre becomes milky, while in a plano-concave cell the periphery is tinged where the thickness is large. There is also the loss of transparency due to the use of polarizers, but this is overcome by having liquid crystal lenses consisting of two single variable refractive index lenses, each one producing a variable focusing effect on the components of the incident light, which are mutually orthogonal. Such a lens is illustrated in Figure 6.

In most of the research work to date, the optimum thickness of the layer should be about 10–100  $\mu\text{m}$  (preferably 50  $\mu\text{m}$ ), when the cell will be transparent and show good performance. But then another problem arises. This is due to the insignificant power change. A lens of 40 mm diameter with a plano-convex configuration and filled with MBBA is given as an example. Figure 11 shows such a lens with  $F_1$ ,  $F_2$ , and  $F_3$  being the refractive surfaces of this lens. According to the calculations and keeping  $F_1$  and  $F_3$  constant, then when the field is off, the power  $F_2$ , which is the refractive surface with the variable power, will have a value of  $F_2 = +2.75 \times 10^{-3} \text{ D}$ . This happens when the thickness of the liquid crystal layer at the centre is 25  $\mu\text{m}$ . By keeping the other surfaces constant and inducing an electric field, the power changes so that  $F_2 = 0.027 \text{ D}$ , which is insignificant. This is due to the very small sag of the lens-cell. The problem can be handled either by using a lens of the Fresnel type, which keeps the layer thin but does not affect the dioptric power of the lens  $F_2$  that much or using more than one layer, probably 4–6 layers sandwiched together. The layers of liquid crystal material will be separated by electrodes formed in a very thin transparent film. Such a configuration will reduce the thickness without affecting the power  $F_2$ .

With regard to the plano-convex or plano-concave configuration proposed by a number of researchers, the lens will obviously suffer from lack of uniformity of the applied field. The lack of uniformity is due to the fact that the thickness at the centre of the lens is not the same as the periphery. The field at the centre will be weaker than the one at the periphery for a plano-convex lens while the opposite is the case for a plano-concave lens. How much this effects the lens performance has not yet been estimated. Okada *et al.*<sup>33</sup> proposed a configuration like the one shown in Figure 12 to tackle this problem.

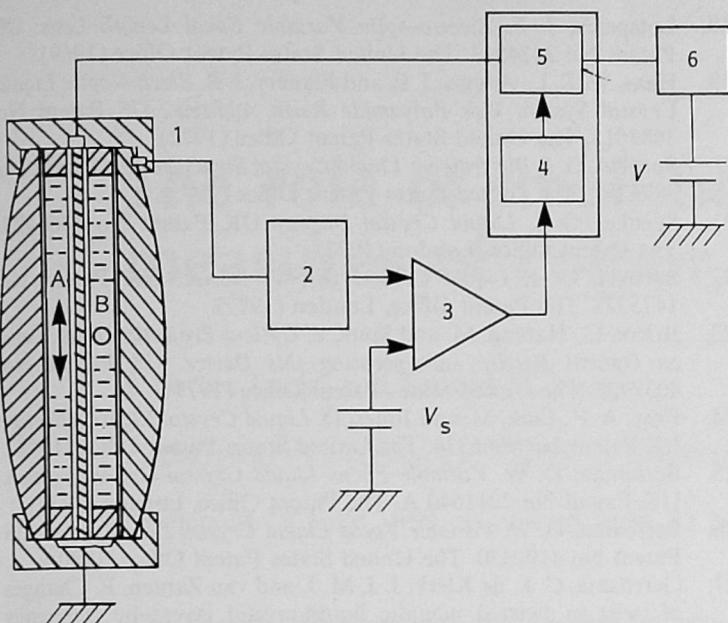


Figure 12 Liquid crystal lens with a specific configuration to avoid the lack of uniformity of the applied field. After reference 33

The last and most serious drawback of the liquid crystal lens is the temperature dependence of its refractive index. The refractive index variation, according to the temperature variation, for a nematic material such as HCB is illustrated in Figure 13<sup>39</sup>. It is clear that the dependence of the extraordinary index ( $n_e$ ) is clearly greater than that of the ordinary index ( $n_o$ ). Above the clearing point in the isotropic phase, birefringence disappears and a third refractive index ( $n_i$ ) is presented. Obviously, according to environmental changes, the appearance of the lens and its performance will change. To keep the refractive index constant, temperature compensation means are needed, as described by Okada *et al.*<sup>33</sup> The temperature sensor (1) could be a thermistor or a thermocouple and it is mounted around the liquid crystal lens cell as shown in Figure 7. If the sensor is a thermistor it should be connected in series with a reference resistor across a constant voltage source of the temperature detecting and processing unit (2). This unit derives a voltage signal in the form of a resistance variation with temperature. In the case of a thermocouple, the output temperature is obtained as a differential signal against a compensated cold contact at the unit (2). In both cases the output from the unit (2) is sent to the comparator (3), where it is compared with the voltage  $V_s$ , which represents a given

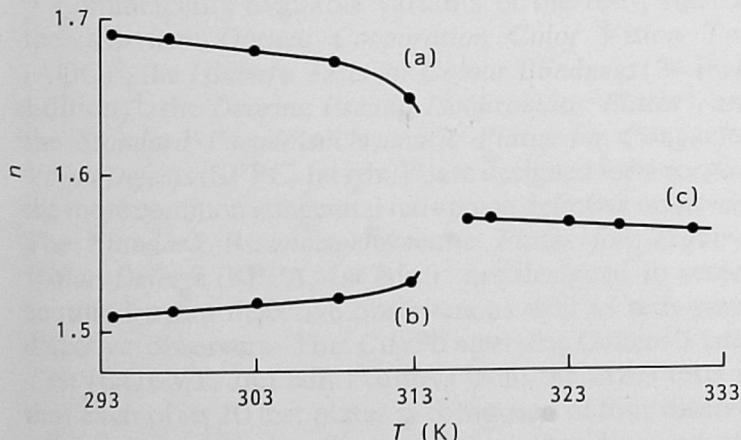


Figure 13 Schematic diagram of the temperature dependence of the refractive indexes of PCB. (a) extraordinary ray index ( $n_e$ ); (b) ordinary ray index ( $n_o$ ); (c) ( $n_i$ ) isotropic phase index. After reference 39

focal length. The output of the comparator (3), which represents a deviation from the given temperature, goes through the correction unit (4) and the variable voltage circuit (5) and any temperature change is compensated for. This takes place by reducing or increasing the voltage level applied by the voltage source V. Instead of a DC/AC converter (6) an oscillator could also be used.

The preselected focal lengths of such a lens can be manually established as shown in Figure 14. In this case three selected focal lengths (distance, intermediate and near vision) were established. The switch S allows different voltages to be applied on the liquid crystal layer from the variable voltage circuit (5) at a given temperature, while to maintain the selected focal length the correction unit (4) is cooperatively connected through the switch S to compensate for any temperature change. The actual number of focal lengths presented by a liquid crystal lens of such configuration is not limited to three and a preselected number of focal lengths can be attained with a similar configuration to that of Figure 14.

Considering the problems mentioned above, it is clear that it is difficult to prepare a liquid crystal lens of high quality and ideal performance. The problem related to the thickness of the lens and consequently to the transparency is the main obstacle to production. This problem could be solved in the near future. However, from a practical point of view, such a lens configuration with all the circuits and units needed for its operation is difficult to envisage mounted on today's fashion frames. It will be bulky and probably unacceptable aesthetically. It is hard to imagine a frame that will have electrodes running through its sides and small batteries to provide the necessary field. Besides its appearance, it is also difficult to envisage how the patient will understand which of the preselected focal lengths would be suitable for clear focus each time an object is viewed. Even if the patient is able to judge correctly, the whole process will not be convenient. It should also be taken into account that during the switching time (changing from one focal length to another) confusion due to the sudden change of the lens power may be an additional drawback.

Although at present liquid crystal lenses might appear alien devices, perhaps their manufacture in the next decade will become a reality. The future of the liquid crystal lens appears promising.

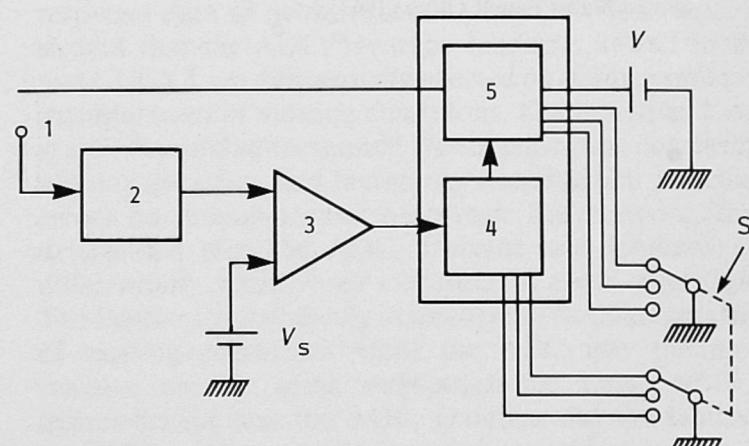


Figure 14 Schematic representation of the detection and compensation methods of the lens configuration proposed by Okada *et al.*<sup>33</sup> (1) Temperature sensor, (2) temperature detecting and processing unit, (3) comparator, (4) correction unit, (5) variable voltage unit. The switch S allows different voltages to be applied by manually changing the position of the switch S, in this case by changing the position of the switch to one of the three preselected focal lengths will be presented

## Acknowledgements

The authors thank Dr M. Beevers for the stimulating discussions on the subject. Mr E. S. Pateras thanks the Greek State Scholarship Foundation (I.K.Y.) from which he is a holder of a scholarship.

## References

1. Gray, G. W. *Molecular Structure and the Properties of Liquid Crystals*. Academic Press, London, pp. 2-3, 17-54, 105-112 (1962).
2. Kelker, H. History of liquid crystals. *Molecular Crystals Liquid Crystals* **21**, 1-48 (1972).
3. Selawry, O. S., Selawry, H. S. and Holland, J. F. The use of liquid cholesteric crystals for thermographic measurement of the skin temperature in man. *Molecular Crystals Liquid Crystals* **1**, 495-501 (1966).
4. Saeva, F. D. *Liquid Crystals: The Fourth State of Matter*. Marcel Dekker, New York, pp. 81-83, 439-456
5. Sullivan, C. M. and Fowler, C. W. Analysis of a progressive addition lens population. *Ophthal. Physiol. Opt.* **9**, 163-170 (1989).
6. Beevers, M. S. The electro-optical Kerr effect in solutions of the nematogen N-(p-Methoxybenzylidene)-p-n-butylaniline. *Molecular Crystals Liquid Crystals* **31**, 333-348 (1975).
7. Labrunie, G. and Roberts, J. Transient behavior of the electrically controlled birefringence in a nematic liquid crystal. *J. Appl. Phys.* **44**, 4869-4874 (1973).
8. Frank, F. C. Liquid Crystals - On the theory of liquid crystals. *Discussions Faraday Soc.* **25**, 19-28 (1958).
9. Sheridan, J. P. and Giallorenzi, T. G. Electro-optically induced deflection in liquid crystal waveguides. *J. Appl. Phys.* **45**, 5160-5163 (1974).
10. Chatelain, P. Alignment method of nematic liquid crystals. *Bull. Soc. Fr. Mineral. Cristallogr.* **77**, 323-328 (1954).
11. Berreman, D. W. Alignment of liquid crystals by grooved surfaces. *Molecular Crystals Liquid Crystals* **23**, 215-231 (1973).
12. Janning, J. L. Thin film surface orientation of liquid crystals. *Appl. Phys. Lett.* **21**, 173-174 (1972).
13. Creagh, L. T. and Kmetz, A. R. Mechanism of surface alignment in nematic liquid crystals. *Molecular Crystals Liquid Crystals* **24**, 59-68 (1973).
14. Dubois, J. C., Gazard, M. and Zann, A. Plasma-polymerised films as orientation layers for liquid crystals. *Appl. Phys. Lett.* **24**, 297 (1974).
15. Skaupy, F. *Apparatus for Refracting Light Rays*. US Patent No 1923891. The United States Patent Office (1933).
16. Gesellschaft Zur Förderung Der Forschung An Der Eidgenössischen Technischen Hochschule (Swiss Body) *Improvements in or Related to Methods of and Means for Amplifying the Light Intensity of an Optically Projected Image*. UK Patent No 808981. The Patent Office, London (1959).
17. Kosanke, K. M. and Kulcke, W. W. *Electro-optical High Speed Adjustable Focusing Zone Plate*. US Patent No 3309162. The United States Patent Office (1967).
18. Lotspeich, J. F. *Electro-optic Variable Focal Length Lens*. US Patent No 3424513. The United States Patent Office (1969).
19. Haas, W. E. L., Adams, J. E. and Flanery, J. B. *Electro-optic Liquid Crystal System with Polyamide Resin Additive*. US Patent No 3687515. The United States Patent Office (1972).
20. Sprokel, G. J. *Birefringent Liquid Crystal Structure*. US Patent No 3876287. The United States Patent Office (1975).
21. Sprokel, G. J. *Liquid Crystal Display*. UK Patent No 1468423. The Patent Office, London (1977).
22. Sprokel, G. J. *Liquid Crystal Display Device*. UK Patent No 1475378. The Patent Office, London (1977).
23. Bricot, C., Hareng, M. and Spitz, E. *Optical Projection Device and an Optical Reader Incorporating this Device*. US Patent No 4037929. The United States Patent Office (1977).
24. Fray, A. F., Link, M. and Jones, D. *Liquid Crystal Light Deflector*. US Patent No 4066334. The United States Patent Office (1978).
25. Berreman, D. W. *Variable Focus Liquid Crystal Optical System*. UK Patent No 2011640 A. The Patent Office, London (1978).
26. Berreman, D. W. *Variable Focus Liquid Crystal Lens System*. US Patent No 4190330. The United States Patent Office (1980).
27. Gerritsma, C. J., de Klerk, J. J. M. J. and van Zanten, P. Changes of twist in twisted nematic liquid-crystal layers by frequency switching of applied electric fields. *Solid State Commun.* **17**, 1077-1080 (1975).
28. Hilsum, C. and Raynes, E. P. *Liquid Crystal Display*. UK Patent No 2012093. The Patent Office, London (1978).
29. Portmann, H. *Liquid Crystal Display Cell with Temperature Compensations*. UK Patent No 2090674. The Patent Office, London (1979).
30. Thomson-Brandt *Variable Focus Liquid Crystal Lens*. UK Patent No 1563113. The Patent Office, London (1980).
31. Sato, S. Liquid-crystals lens-cell with variable focal length *Jpn. J. Appl. Phys.* **18**, 1679-1683 (1979).
32. Sato, S., Sugiyama, A. and Sato, R. Variable-focus liquid-crystal Fresnel lens. *Jpn. J. Appl. Phys.* **24**, L626-L628 (1985).
33. Okada, T., Nakamura, T., Nakamura, K., Nishioka, K., Kouchi, T., Yamamoto, H. and Tomabechi, H. *Spectacle Lens*. UK Patent No 2163864 A. The Patent Office, London (1986).
34. Okada, T., Nakamura, T., Nishioka, K., Yamamoto, H., Kouchi, T. and Tomabechi, H. *Liquid Crystal Lens Having a Variable Focal Length*. UK Patent No 2169417. The Patent Office, London (1986).
35. Okada, T., Shimazu, H., Toda, A. and Sato, S. *Liquid Crystal Lenses*. UK Patent No 2187567. The Patent Office, London (1987).
36. DeGennes, P. G. Long range order and thermal fluctuation in liquid crystals. *Molecular Crystals Liquid Crystals* **8**, 325-345 (1969).
37. Chen, D. H., James, P. G. and Luckhurst, G. R. Order in the nematic mesophase. *Molecular Crystals Liquid Crystals* **8**, 71-83 (1969).
38. Heilmeier, G., Zanoni, L. A. and Barton, L. A. Dynamic scattering: A new electro-optic effect in certain classes of nematic liquid crystals. *Proc. IEEE* **56**, 1162-1171 (1968).
39. Davies, M., Moutran, R., Price, A. H., Beevers, M. and Williams, G. Dielectric and optical studies of a nematogen 4,4-n-heptyl-cyanobiphenyl. *J. Chem. Soc. Faraday Trans. II* **72**, 1447-1458 (1976).

This document is a scanned copy of a printed document. No warranty is given about the accuracy of the copy. Users should refer to the original published version of the material.