Liquid-Crystal Lens-Cells with Variable Focal Length

JAPANESE JOURNAL OF APPLIED PHYSICS
VOL. 18, NO. 9, SEPTEMBER, 1979 pp. 1679–1684

Liquid-Crystal Lens-Cells with Variable Focal Length

Susumu SATO

Department of Electronic Engineering, Mining College, Akita University, Tegata Gakuencho 1-1, Akita 010

(Received March 12, 1979)

Liquid-crystal cells shaped like a plano-convex lens or a plano-concave lens are prepared. The focal length can be varied from the value f_e for an extraordinary ray, where the liquid-crystal cell takes a homogeneous alignment, to f_o for an ordinary ray, where it takes a homeotropic alignment, by applying an electric field or a magnetic field across the lens-cell. The focal length in the lens-cell with the homogeneous alignment can also be switched between f_e and f_o. This is done by switching the direction of polarization of the incident light by applying a voltage across a TN cell sandwiched between the polarizer and the lens-cell. Since the thickness of the liquid-crystal layers increases in the lens-cells, the optical transmission properties are investigated as a function of the cell thickness.

§1. Introduction

It is well-known that liquid-crystal cells in which molecules are uniformly aligned along their long axes in the same direction have optical properties similar to those of uniaxial crystals. Since the molecular orientations in the liquid-crystal cells can easily be controlled by applying a relatively low potential, many investigations into their practical application as display devices have been carried out.[1-3] Recently, applications as optical devices such as thin-film optical waveguides[4,5] and light deflection devices[6,7] have been reported for liquid crystals.

When a person's ability to adjust the focal lengths of his eyes has deteriorated because of presbyopia or eye diseases, he needs two or more pairs of glasses in order to see an object at a short distance, such as when reading, or at a long distance, such as when looking out over a wide view. Particularly when the crystalline lenses of the eyes have been removed because of cataracts, a greater number of pairs of glasses are needed. This is extremely inconvenient for the sufferer from such eye disorders. One solution to this problem is to prepare thin, lightweight lenses with variable focal lengths, operated by low voltages with low power dissipation. Lenses with these characteristics may also be useful in auto-focusing cameras.

Since liquid-crystal cells are usually thin and light and are characterized by low power dissipation, they seem to satisfy the above conditions. In this paper, the preparation of lens-shaped liquid-crystal cells is described, and their optical properties are investigated. The mechanism for varying the focal lengths of these cells by applying an electric field or a magnetic field across the cells is described, as is a lens with variable focal length prepared by combining a TN (twisted nematic)[2] cell with a lens-shaped cell. The thickness of the liquid-crystal layer in these lens-shaped cells is large compared with that of ordinary liquid-crystal cells such as those used in display devices. Therefore the optical transmission properties are also investigated using cells with very thick liquid-crystal layers.

§2. Experimental Procedure

The nematic liquid crystal MBBA (*p*-methoxybenzylidene-*p*′-*n*-butylaniline), MEE mixtures of MBBA, EBBA (*p*-ethoxybenzylidene-*p*′-*n*-butylaniline), and EBAB (*p*-ethoxybenzylidene-*p*′-aminobenzonitrile) (2:2:1 by weight ratio); and PCB (*p*-*n*-pentyl-*p*′-cyanobiphenyl) were used in this study. The liquid-crystal lens-cells were constructed as follows; liquid crystals were put into cells fabricated from an SnO_2-coated glass plate, a space of suitable thickness, and a concave or a convex glass-lens. The focal lengths of the glass lenses used were between 67 mm and 678 mm for the plano-convex lens, and between −85 mm and −244 mm for the plano-concave

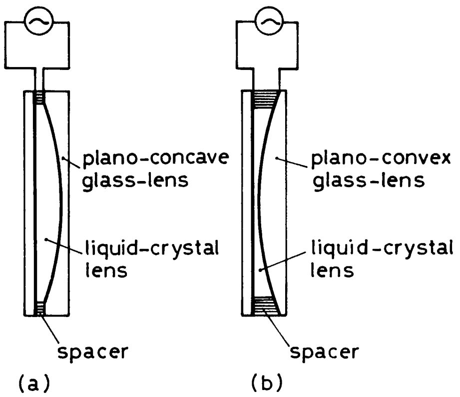

Fig. 1. Structure of the liquid-crystal lens-cells. (a) plano-convex cell, (b) plano-concave cell.

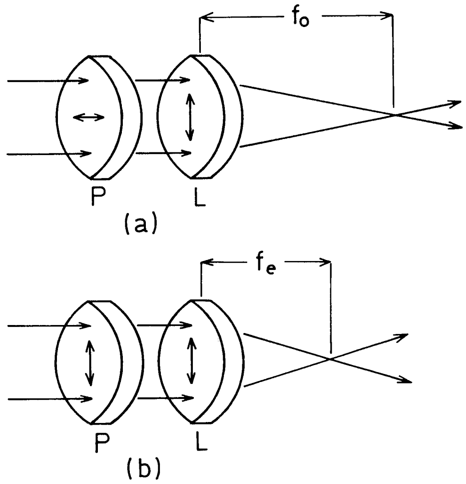

Fig. 2. Relationship between the direction of polarization and the optical axis of the liquid-crystal cells. (a) Ordinary ray, (b) Extraordinary ray. P: polarizer, L: liquid-crystal lens-cell.

lens. Then the liquid-crystal lens-cells were shaped like a plano-convex lens or a plano-concave lens as shown in Fig. 1(a) and (b) respectively. The glass plate and the glass lens were treated by organic silane compounds and by rubbing to give the liquid-crystal molecules a homogeneous texture.

The composite focal lengths of the liquid-crystal lens-cell and the glass lens were measured with two beams of an He–Ne laser at a distance of 8 mm, and the focal length f of the liquid-crystal lens-cell alone was calculated from the following fundamental formula in geometrical optics

$$f=\left(\frac{1}{f_{\rm exp}}-\frac{1}{f_{\rm g}}\right)^{-1}. \qquad (1)$$

where $f_{\rm exp}$ is the composite focal length and $f_{\rm g}$ is the focal length of the glass lens.

To examine the transmission light intensity as a function of the thickness of the liquid-crystal layer, plane-parallel cells with homeotropic or homogeneous alignment were constructed using glass plates and spacers 9 μm$\sim$800 μm thick. The dependence of transmission light intensities and transmission spectra in these cells on the cell thickness was measured using a double-beam type spectrometer.

§3. Experimental Results and Discussion

3.1 *Optical properties of liquid-crystal lens-cells and fabrication of liquid-crystal lens with variable focal length*

The relationship between the direction of polarization of the incident light and the optical axis of the liquid-crystal cell is shown in Fig. 2. The liquid-crystal cell becomes the lens with the refractive index for an ordinary ray in the case shown in Fig. 2(a). It becomes the lens with the refractive index for an extraordinary ray in the case shown in Fig. 2(b). That is, the liquid-crystal cells could be used as a lens with two different focal lengths if the direction of polarization of the incident light were switched perpendicular to or parallel to the direction of the optical axis of the liquid-crystal cells. The same switching of the focal length could also be obtained if the liquid-crystal lens-cell were replaced by uniaxial transparent crystals.

Liquid-crystal lens-cells with the homogeneous alignment having various radii of curvature were prepared using MBBA. The focal length for the ordinary ray ($f_{\rm o}$) and that for the extraordinary ray ($f_{\rm e}$) were measured at room temperature and are shown in Fig. 3 as a function of the radius of curvature R. In this figure, the area where both R and f are positive (the first quadrant) corresponds to the convex lens, and the area where both are negative (the third quadrant) corresponds to the concave lens. From the fundamental formula in geometrical optics, the focal length of the thin plano-convex lens (for the plano-concave lens, R may be considered to be negative) with refractive index n and radius of curvature R is given as

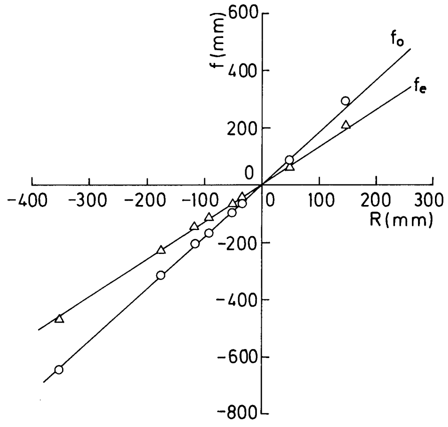

Fig. 3. Focal lengths f of the lens-cells prepared with MBBA versus radius of curvature R. The solid lines show the theoretical plots calculated from eq. (2) and the open circles and triangles show the experimental results.

$$f=\frac{R}{n-1}. \tag{2}$$

Therefore f_o and f_e can be calculated from eq. (2) with the refractive indices represented as n_o and n_e for the ordinary ray and the extraordinary ray respectively. Each solid line in Fig. 3 shows the plots calculated from eq. (2) using the values $n_o=1.545$ and $n_e=1.755$ for MBBA,[8] and the open circles and triangles show the experimental results. It is seen that the focal lengths of the prepared liquid-crystal lens-cells nearly coincide with the theoretical values.

The temperature dependence of the focal lengths of the liquid-crystal plano-concave lens-cell ($R=-121$ mm) is shown in Fig. 4 (the temperature dependence of the focal length of glass lenses is very small compared with that of the liquid-crystal lens-cell). Since the temperature dependence of n_e is generally larger than that of n_o, the temperature dependence of f_e is larger than that of f_o. At temperatures above the clearing point, the liquid-crystal becomes an isotropic liquid and the birefringence disappears; therefore the liquid-crystal cell becomes a normal lens with one focal length.

When an ac voltage (1 kHz) is applied across the P-type liquid-crystal lens-cells with the homogeneous alignment where the direction of polarization of the incident light is parallel to the optical axis of the liquid-crystal cell (as

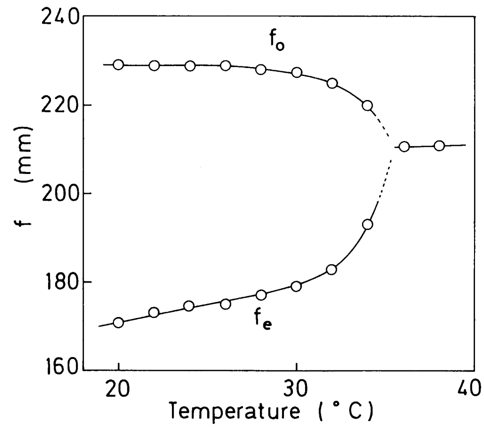

Fig. 4. Temperature dependence of f_e and f_o of the plano-concave lens-cell prepared with PCB.

shown in Fig. 2(b)), the apparent refractive index varies by the ECB (electrically controlled birefringence) effect,[3] so the focal length of the lens-cell can be controlled. The change of the focal length of the liquid-crystal plano-concave lens-cell ($R=-121$ mm) is shown in Fig. 5 as a function of the applied voltage. It can be seen that the focal length of the liquid-crystal cell can be varied continuously in some ranges from f_e to f_o. Since the thickness of the liquid-crystal lens-cell is not constant in the radial direction, in contrast to plane-parallel-type cells, the electric field inside the cell is non-uniform. Therefore the focal length of the cell at the center may be different from that at the periphery of the liquid-crystal lens-cells. This effect will be discussed elsewhere.

The focal length can be varied by applying a magnetic field as well as an electric field, since

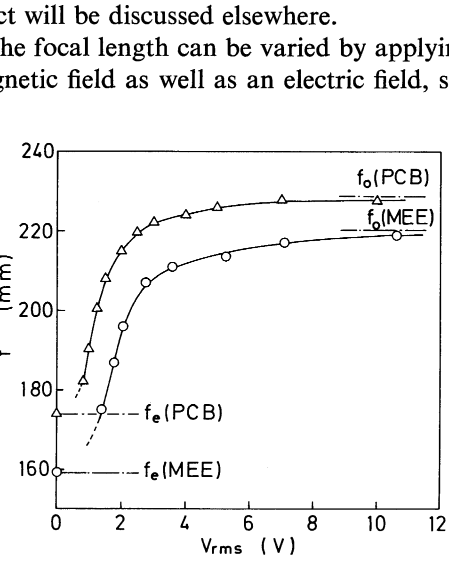

Fig. 5. Change of focal length of the plano-concave lens-cell as a function of applied ac voltage (1 kHz).

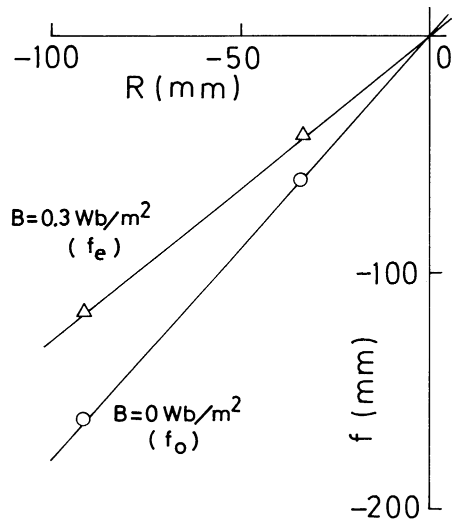

Fig. 6. Switching of the focal length from f_o to f_e by applying a magnetic field to the plano-concave lens-cells prepared with MBBA. Solid lines show the theoretical plots calculated from eq. (2). Open circles: $B=0$ Wb/m^2(f_o), triangles: $B=0.3$ Wb/m^2(f_e).

the molecular orientation can be controlled by a magnetic field. For instance, switching of the focal length from f_o to f_e in the liquid-crystal plano-concave lens-cells with the homeotropic alignment is shown in Fig. 6 when a magnetic field sufficiently greater than the threshold value is applied parallel to the surface of the lens-cell. The direction of polarization of the incident light is taken as the direction of the applied magnetic field.

One of the disadvantages in the liquid-crystal lens-cells is that the response and recovery properties are very slow, because the thickness of the liquid-crystal layer is very large compared with that of the usual liquid-crystal cells used in display devices (namely about 10 μm). For example, in the plano-convex lens-cell prepared from MBBA with the focal length of 200 mm for the ordinary ray, the radius of curvature calculated from eq. (2) is 109 mm. Then the thickness of the liquid-crystal layer at the center of the cell becomes 460 μm when the diameter of the cell is 20 mm. The response time can be reduced if a higher potential is applied across the cell; however, the recovery time is independent of the applied potential and increases as a function of the square of the cell thickness.[9] Therefore a very long time is necessary for the recovery process at the centre of the plano-convex lens-cell and at the periphery of the plano-concave cell.

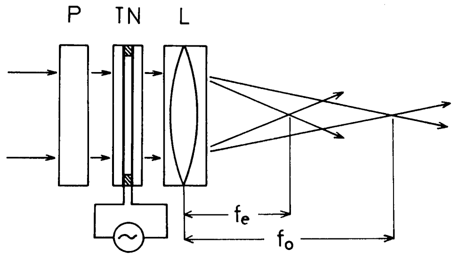

Fig. 7. Liquid-crystal lens-cells with variable focal lengths using the TN cell.

The focal length of the liquid-crystal lens-cells with the homogeneous alignment can be varied by switching the direction of polarization of the incident light between the ordinary ray and the extraordinary ray without applying an electric field or a magnetic field across the lens-cells (Fig. 2). Therefore the focal length of the lens-cell can be switched between f_o and f_e by applying a voltage across a TN cell inserted between the polarizer and the liquid-crystal lens-cell, as shown in Fig. 7. The merit of this system is that the switching voltage is low and the response time as well as the recovery time are short compared with the system in which an electric field is applied across the liquid-crystal lens-cell. 2^n focal lengths can be selected in the n-fold multi-layered structures made by stacking TN cells and liquid-crystal lens-cells.

The variable range of the focal lengths defined as $\Delta f/(f_o+f_e)$ is derived from eq. (2),

$$\frac{\Delta f}{f_o+f_e}=\frac{f_o-f_e}{f_o+f_e}=\frac{n_e-n_o}{n_e+n_o-2}. \qquad (3)$$

In order to expand the variable range of the focal lengths, it is necessary that liquid-crystals with large values of birefringence ($\Delta n=n_e-n_o$) must be used.

Since liquid-crystals have a large wavelength dispersion of the refractive index and a remarkable optical anisotropy, there are several aberrations such as chromatic, spherical, etc. These problems are very important in practical applications of the liquid-crystal lens-cells and will be discussed elsewhere.

3.2 *Relationship between the thickness of the cell and the transmission light intensity*

As previously mentioned, the thickness of the liquid-crystal layer in liquid-crystal lens-cells is often very large. The transmission of the incident light is expected to decrease in such thick cells, since the absorption by the liquid-crystals increases and the scattering effect becomes large because the order of the molecular alignment in the liquid-crystal cell decreases. The liquid-crystal lens-cells prepared from MBBA are tinged milky-yellowish-white at the center of the plano-convex lens-cell and at the peripheral parts of the plano-concave lens-cell. The relationship between the transmission light intensity and the thickness of the spacer in the cells with the homeotropic or homogeneous alignment is shown in Fig. 8. The measurement was carried out at 30 °C for MBBA and at 25 °C for PCB, and the wavelength used was 550 nm. The transmission light intensities in this figure are normalized by the transmission intensities in the isotropic phase for each liquid-crystal cell to compensate for absorption. Absorption by the liquid-crystals increases abruptly in the short wavelength region ($\lesssim$420 nm for MBBA and a much shorter wavelength region for PCB), but the absorption loss at about 550 nm is very small compared with the loss due to scattering. It can be seen that the transmission light intensity decreases as the liquid-crystal cell becomes thicker, and this effect is severe in the cells with the homogeneous alignment. Since the molecular orientation in the cells with the homeotropic alignment is apparently one-dimensional but is two-dimensional in the cells with the homogeneous alignment, the degree of the molecular orientation in the latter cells is worse and the transmittance is smaller than that of the former cells.

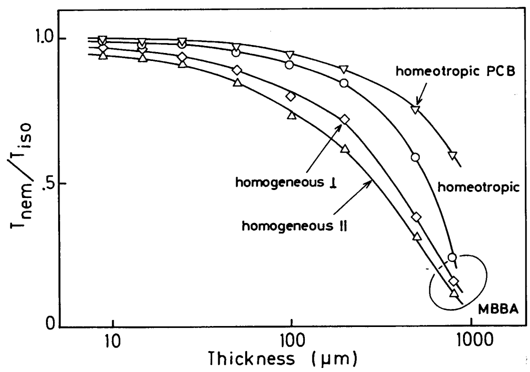

Fig. 8. Relationship between the normalized transmission intensity and the thickness of the spacer. Homogeneous $\perp$: polarization is perpendicular to the optical axis. Homogeneous //: polarization is parallel to the optical axis.

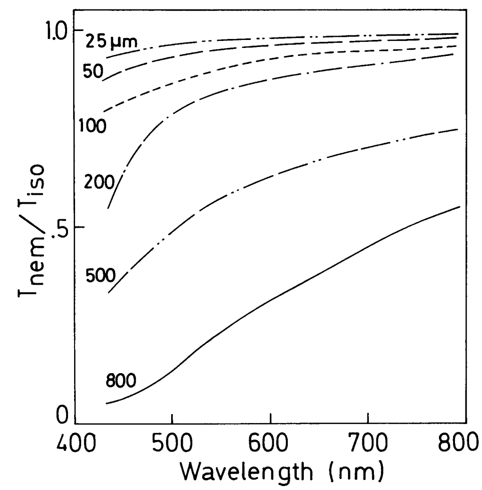

Fig. 9. Transmission spectra of homeotropically-aligned MBBA cells with different thicknesses of liquid-crystal layers.

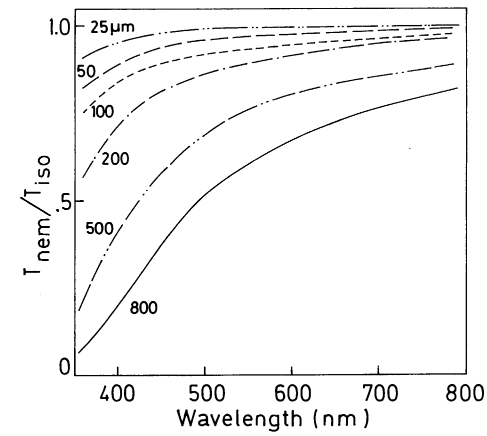

Fig. 10. Transmission spectra of homeotropically-aligned PCB cells with different thicknesses of liquid-crystal layers.

The dependence of the transmission spectra on the cell thickness is shown in Fig. 9 for the homeotropically aligned cells prepared with MBBA and in Fig. 10 for the cells prepared with PCB, where each spectrum is also normalized by the transmission light intensities in the isotropic phase. In these figures, in spite of compensation for absorption, transmission in the short wavelength region decreases, and this decrease of the transmission becomes more evident as the thickness of the liquid-crystal cell increases. The thickness of the liquid-

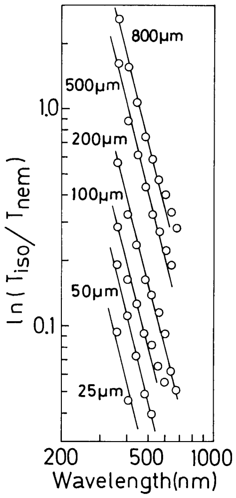

Fig. 11. Relationship between $\ln(T_{iso}/T_{nem})$ and wavelengths in homeotropically-aligned PCB cells.

crystal, which is related to both the diameter and the radius of curvature in the lens-cells, is therefore subject to some limitation. To use liquid-crystals as lens-cell, the liquid-crystals must have transparent and flat transmission spectra in the visible range. One such liquid-crystal is PCB, which has no absorption band in the visible range and is more transparent than MBBA.

The decrease of transmission observed when the liquid-crystal layer becomes thick may depend on the order parameter of the liquid-crystals or the surface treatment of the substrates for the molecular orientation. In Fig. 11, $\ln(T_{iso}/T_{nem})$ is plotted as a function of wavelength. Since the gradient of each line on the log-log plots is nearly -4, one factor for this decrease of transmission seems to be Rayleigh-type scattering originating from the fluctuation of molecules.[10]

§4. Conclusions

Liquid-crystal cells with homogeneous alignment shaped like plano-convex or plano-concave lenses are constructed, and their optical properties are investigated. The focal length of the liquid-crystal lens-cells can be varied by applying an electric or magnetic field across them.

Liquid-crystal lens-cells with variable focal length are constructed by inserting a TN cell between the polarizer and the lens-cell. The switching voltage applied across the TN cell is low and both the response time and the recovery time are short. Many values of the focal lengths can be selected in multi-layered structures formed by combining TN cells and lens-cells.

The transmission light intensity and the transmission spectra of liquid-crystal cells with very thick layers are investigated. The transmission decreases in the short wavelength region as the liquid-crystal layer increases even if the absorption effect is compensated for.

To prepare liquid-crystal lens-cells with high quality and widely variable focal lengths, the liquid-crystals must have a large birefringence and must be transparent in the visible range, and the transmission must not decrease when the liquid-crystal cell becomes thick.

Acknowledgments

The author would like to thank Professor Masanobu Wada of Tohoku University for continuous encouragement and Professor Daitaro Okuyama of Akita University for useful advice.

References

1) G. H. Heilmeier, L. A. Zanoni and L. A. Barton: Proc. IEEE **56** (1968) 1162.
2) M. Schadt and W. Helfrich: Appl. Phys. Lett. **18** (1971) 127.
3) M. F. Schiekel and K. Fahrenschon: Appl. Phys. Lett. **19** (1971) 391.
4) C. Hu, J. R. Whinnery and N. M. Amer: IEEE J. Quantum Electron. **QE-10** (1974) 218.
5) J. P. Sheridan and T. G. Giallorenzi: J. Appl. Phys. **45** (1974) 5160.
6) A. P. Fray and D. Jones: Electron. Lett. **11** (1975) 7.
7) S. Sato and A. Kikuchi: Oyo Buturi **45** (1976) 938 [in Japanese].
8) G. Labrunie and S. Valette: Appl. Opt. **13** (1974) 1802.
9) G. Labrunie and J. Robert: J. Appl. Phys. **44** (1973) 4869.
10) S. Chandrasekhar: *Liquid Crystals* (Cambridge University Press, 1977) p. 70, 155.