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Variable-Focus Liquid-Crystal Fresnel Lens

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Liquid-crystal lens-cells shaped like a plano-convex Fresnel lens with homogeneous alignment are prepared. Their focal length can be varied from the value f_e for an extraordinary ray to nearly f_o for an ordinary ray by applying an electric field across the cell. The response and recovery times within several seconds are attained in the liquid-crystal lenses. More transparent ($\gtrsim$80%) variable-focus liquid-crystal lenses are achieved in the double-layered structure of two identical liquid-crystal Fresnel lenses with a mutually orthogonal optic axis.

§1. Introduction

Thin and lightweight lenses with variable focal lengths are needed by persons who have to wear two, three or more pairs of glasses because of presbyopia or eye diseases such as cataracts. This type of lens may also be useful in other kinds of optical equipment.

It is well known that nematic liquid-crystal cells are usually thin and light, and are characterized by low power dissipation. The molecular orientation, that is, their refractive index can be changed by applying a relatively low potential across the cells. A lens made from liquid crystal is useful for this purpose.

Liquid-crystal cells shaped like a plano-convex lens or a plano-concave lens have been made by using nematic liquid crystals with positive dielectric anisotropy.[1] Their focal length could continuously be varied from the value f_e of an extraordinary ray (homogeneous alignment) to f_o of an ordinary ray (homeotropic alignment) by applying an electric field across the lens-cell.[1] However, there are some disadvantages when this type of liquid-crystal lens is put into practical use: the response and recovery properties in the lens are very slow, because the thickness of the liquid-crystal layer becomes extremely large at the center of a convex lens-cell or at the peripheral part of a concave lens-cell in comparison with that of a usual liquid-crystal display cell. In addition, the transmission of incoming light is reduced according to the increase in thickness of the liquid-crystal cell by the absorption and/or scattering effect.

The response and recovery properties and the transmittance can be improved by decreasing the effective thickness of the liquid-crystal layers. In this paper, we describe improvement in the properties of variable-focus lenses by adopting the liquid-crystal layer as the Fresnel structure. Variable focus lenses without polarizers are made using two identical liquid-crystal Fresnel lenses with orthogonal optic axis. Some properties of these Fresnel-type liquid-crystal lenses are investigated.

§2. Experimental Procedure

The nematic liquid crystals K15 and E7 (Merck) with positive dielectric anisotropy were used in this work. Samples with homogeneous molecular orientation were prepared using Mylar spacers of suitable thickness between ITO coated glass plates and a concave Fresnel lens. A typical value of the groove depth of the Fresnel lenses was within about 100 μm, the pitch was about 200 μm and the focal length was -76 mm. Semitransparent Au films or ITO films as an electrode were deposited onto the surface of the Fresnel lens. The composite focal lengths of the liquid-crystal lens and the Fresnel lens were measured with a collimated beam of an He–Ne laser or with a lens meter (Topcon LM-P4). The transmittance of the liquid-crystal lens was measured with a lens-transmission meter (Hoya Universal Lens Tester Model ULT-1000).

Measurements were made of response times, which were defined as the period required for the transmitted light intensity detected at the focal point by a photo-cell to decrease to 20% of its steady state value when the voltage was applied across the lens-cell. Recovery times were measured as the period required for the light intensity to increase to 80% when the voltage was removed. All measurements were made at room temperature.

§3. Experimental Results and Discussion

The change in focal length at the central part of a Fresnel-type liquid-crystal lens-cell is shown in Fig. 1 as a function of the applied voltage. The parameter shown in the figure is the frequency of applied voltage. It is seen that the focal length of the liquid-crystal lens can continuously be varied from f_e to nearly f_o. The value of applied voltage required to change the focal length becomes larger as the frequency increases because of the relatively high electrode series resistance of the lens surface in this work. However, there is no need to consider the frequency dependent properties of the lens-cells if the driving frequency is kept below a few kHz.

A collimated input laser beam 10 mm in diameter can be converged by the liquid-crystal lens into a focus which is less than 1 mm in diameter for the extraordinary ray. The focussing properties under the voltage application are somewhat worse than those for the extraordinary ray. These properties also depend on the precision of the plastic Fresnel lens itself.

Figure 2 shows the response and recovery times plotted on a semilogarithmic scale as a function of the aplied

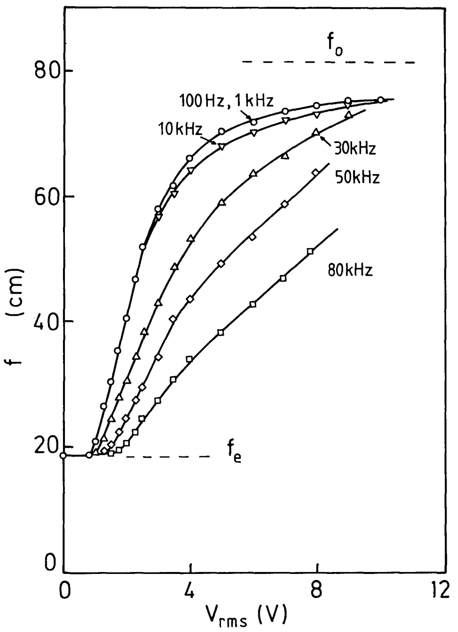

Fig. 1. Change of focal length of the plano-convex Fresnel-type liquid crystal lens cell as a function of applied voltage (K15).

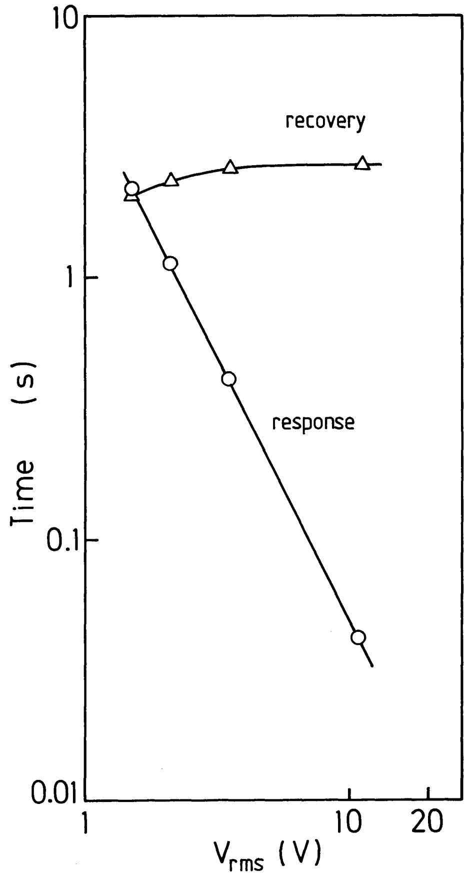

Fig. 2. Response and recovery times as a function of applied voltage (E-7).

voltage (1 kHz). A linear relation is obtained in the response properties as the voltages are increased. In contrast, the decay time remains nearly constant. It is seen that, using the Fresnel structure, the response and recovery properties are extremely reduced in comparison with those reported previously. That is, when the plano-convex liquid-crystal lens with a diameter of 20 mm and a focal length of 200 mm was prepared, the thickness of the liquid-crystal layer at the center of the cell became about 500 μm,[1] which is about 10 times larger than that of the maximum value in the Fresnel-type lens-cell. Since the response and recovery times increase as a function of the square of the cell thickness,[2] an improvement of more than two orders of magnitude can be attained in the same size cells by adopting the liquid-crystal layer as the Fresnel structure. Further improvement can be attained by using smaller grooves in the Fresnel structure. Furthermore, there are no limitations on construction of the large size Fresnel-type liquid-crystal lens-cells. The response and recovery properties can also be reduced by the modulation method of bias voltages.[3]

In addition to the response and recovery properties, the transparency of the lens becomes important when the liquid-crystal lens is practically applied. Transmittance of the ITO-coated liquid-crystal lens as measured for the visible range is about 90%. However, a polarizer is indispensable for the above mentioned liquid-crystal lens, since the polarization of the incident light has to be parallel to the direction of the optic axis of the liquid-crystal cell. Transmittance of the polarizer is usually 30%–40%, so it is hard to make a light lens in this system.

If two identical liquid-crystal lenses are combined with a mutually orthogonal optic axis, the focal length for the extraordinary ray incident on the first lens-cell can be varied by the first liquid-crystal lens. However, the focal length of the second lens-cell is unchanged, since the incident light on the second lens becomes an ordinary ray. The focal length for the ordinary ray incident on the first lens-cell is unchanged, but it becomes the extraordinary ray at the second lens-cell and the focal length can be varied by the second liquid-crystal lens. Therefore, this double-layered lens-cell becomes a more transparent variable focus lens for an incident light with any polarization and also for an unpolarized natural light. Figure 3 shows the change in focal length of a double-layered liquid-crystal Fresnel lens as a function of the aplied voltage (1 kHz). The transmission efficiency of the double-layered ITO-coated liquid-crystal lenses is about 82%. Their transient properties are nearly equal to those shown in Fig. 2.

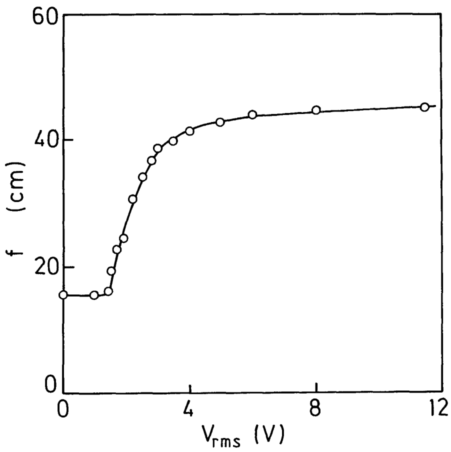

Fig. 3. Change of focal length of the double-layered liquid-crystal Fresnel lens as a function of applied voltage (E-7).

§4. Summary

Homogeneously aligned liquid-crystal cells shaped like plano-convex Fresnel-type lenses were constructed and their optical properties were investigated.

A steep reduction of the response and recovery properties can be obtained in these Fresnel-type liquid-crystal lenses, and the focal length can also be continuously varied from f_e to nearly f_o.

More transparent variable-focus lenses without polarizers are achieved in the double-layered structure of two identical liquid crystal lens cells with mutually orthogonal optic axis.

Acknowledgement

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