Flexible Ferroelectric Liquid Crystal Display Devices Using Thin Plastic Substrates Fastened by Polymer Walls and Networks

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Abstract

We fabricated a flexible ferroelectric liquid crystal (FLC) device containing polymer walls and networks which fix plastic film substrates. The device using 100- μm -thick substrates could be bent in a radius of 7mm without disordering the FLC alignment. When sandwiched between polarizers a roll-up display with high-speed grayscale capability for moving-image displays was created.

1. Introduction

Ferroelectric liquid crystal (FLC) devices using plastic substrates have the major advantage of enabling flexible displays with moving-image capability. To realize FLC devices using flexible substrates, one of the important issues is the maintenance of the fragile smectic layer structure of the FLC. Recently, an FLC device with plastic substrates which were supported by etched spacers was proposed as a flexible display [1]. It was also reported that a flexible display using FLC polymer had a high mechanical stability against bending [2].

However, FLC devices generally are difficult to operate in a grayscale mode because of the bistable nature of the changing FLC alignment [3]. We have already developed a flexible FLC device containing polymer walls and networks [4]. The device had a grayscale capability which was induced by the fine polymer networks dispersed in the FLC [5,6]. It also had a high mechanical stability against bending because the polymer walls fixed both substrates [7].

In this report, we describe in detail the fabrication method, the electro-optic properties and the display capability of the bent device. We also discuss the bending tolerance of our flexible FLC device using thin film substrates.

2. Operation principle

The structure of our flexible FLC device is shown in Fig.1. A composite film of FLC and polymer networks is sandwiched between rubbed alignment layers on substrates with transparent electrodes (ITO; In_2O_3:Sn). The lattice-patterned polymer walls fix both flexible substrates and maintain a constant thickness of the composite film.

When a voltage is applied to the ITO electrodes, the FLC molecular alignment direction switches according to the applied voltage polarity. The polymer networks anchor the FLC molecules and spatially change the threshold voltage for bistable switching in a small area [5,6]. As a result, μm-sized switching domains are induced by applied voltages, and hence, light transmitted through the device between crossed polarizers is modulated analogously.

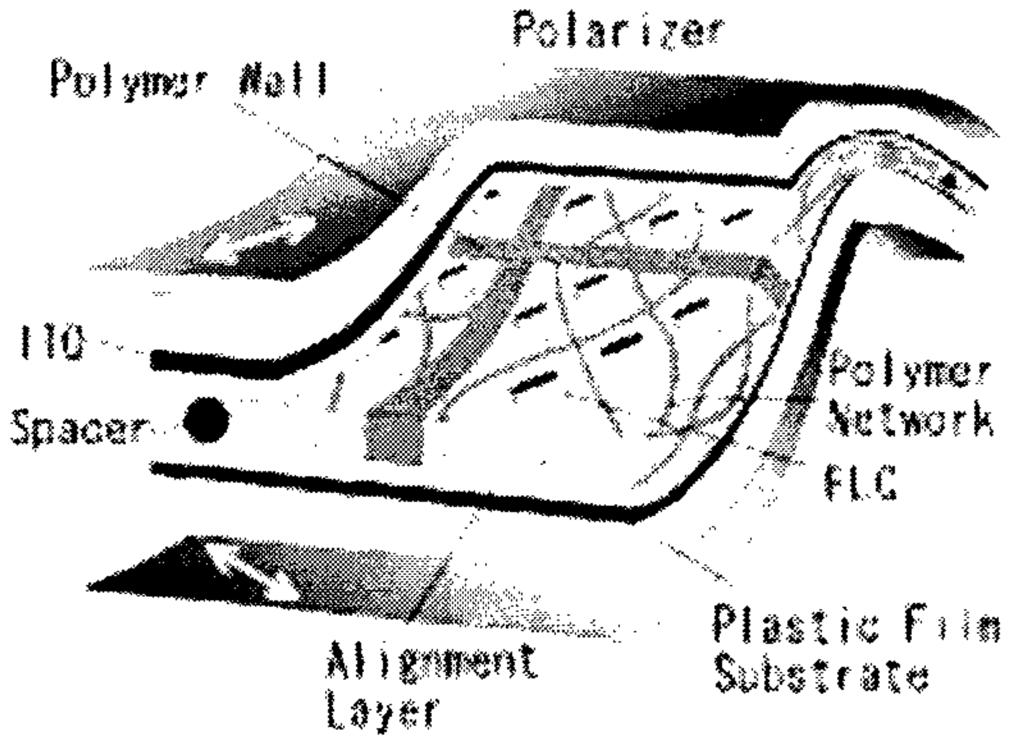

Figure 1 Schematic of the flexible FLC device

3. Device fabrication

The composite film was fabricated by photopolymerization-induced phase separation using two-step irradiation of ultraviolet (UV) light, as shown in Fig.2. A polycarbonate substrate with a rubbed polyimide alignment layer was coated with a solution of an FLC mixture (CS-1030, Chisso) and a liquid crystalline monomer (UCL-001, DIC) with 2-μm-sized spacers by a flexographic printing method [8]. After being laminated with another substrate by using a roller, the solution was heated to a temperature where it exhibited an isotropic phase, and was then irradiated with UV light through a photomask to form polymer walls without optical anisotropy, as shown in Fig.2(a). After that, uniform UV light was irradiated onto the solution in a nematic phase without the photomask to form polymer networks aligned to the rubbing direction (Fig.2(b)).

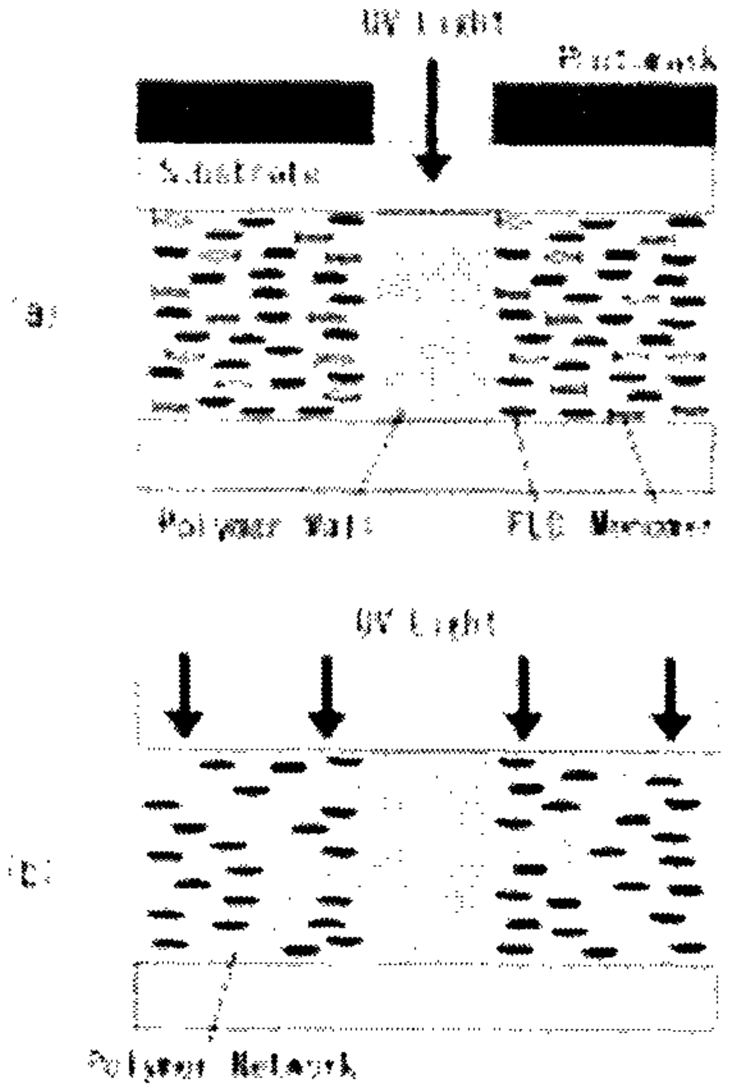

Figure 2 Two-step irradiation process using UV light

Figure 3 shows a confocal laser scanning microscope photograph of the polymer structures adhering to the surface of the substrate. It was confirmed that the polymer walls and networks were separately formed in the device plane. The width and interval of the formed polymer walls were 15μm and 250μm, respectively.

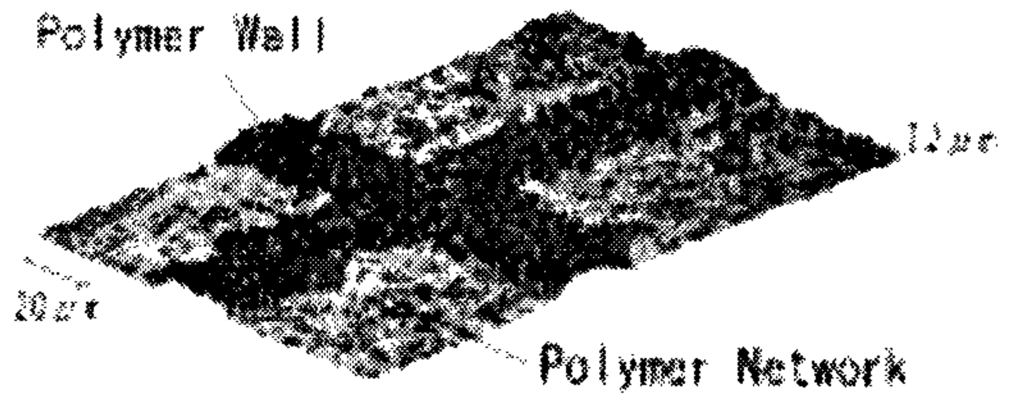

Figure 3 Surface morphology of the polymer walls and networks

4. Bending tolerance

We examined the bending tolerance of the device as follows. First, a small rectangular device (10mm × 60mm) sandwiched between two flexible films was wound uniformly around a solid column of radius R. After the device was removed from the flexible films, the spatial uniformity of the light transmitted through the flat-state device was observed under crossed polarizers to examine the disorder of the FLC alignment. The bending tolerance was evaluated by measuring the minimum R for which no disorder of the FLC alignment occured.

In the case of a device with 200-μm-thick substrates, the FLC molecular alignment was disordered at the edges of the device when R was less than 30mm, because exfoliation of the polymer walls occurred in those areas. It was also found that the areas of exfoliated polymer walls spread to the center of the devices after being bent in smaller radii. We believe that shearing strain concentrated in the device edges caused exfoliation of the polymer walls.

To reduce shearing strain when the device is bent, we fabricated devices using more flexible 100-μm-thick substrates. In the bending test, the uniformity of the FLC alignment in the device was maintained when R was 7mm. It was also found that the bending tolerance does not depend on the FLC alignment direction. Figure 4 shows the results we observed for flat-state devices between polarizers after being bent in a radius of 7mm. No spatial change of light transmittance due to FLC alignment disorder in the devices was observed. In addition, the device could be bent both convexly and concavely without any FLC alignment change because both substrates were fixed by the polymer walls.

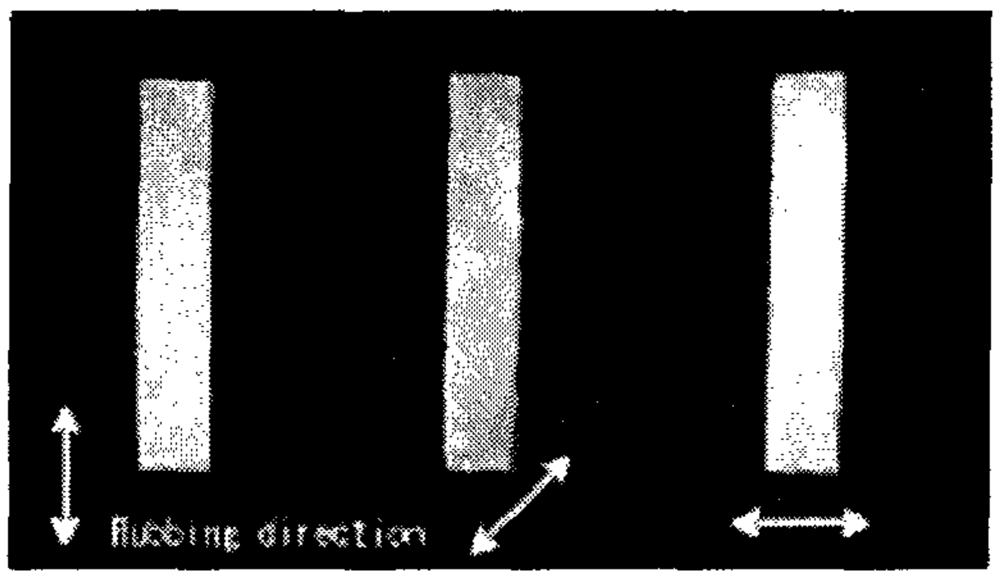

Figure 4 FLC devices with different rubbing directions between crossed polarizers after being bent to a radius of 7mm

To investigate the distortion of the FLC molecular alignment due to bending, the central area of the bent device was observed with a polarizing microscope. Figure 5(a) shows a polarizing microscope photograph of the FLC alignment in a device which was bent with a radius of curvature of 7 mm. The FLC alignment change was not seen in the bent device, through comparison with the same area of the device in a flat condition (Fig.5(b)).

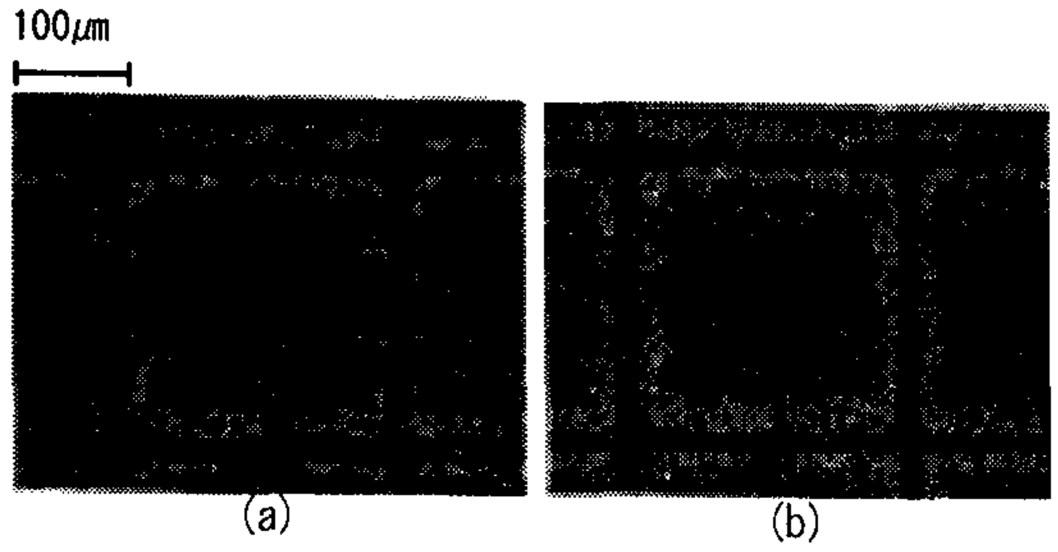

Figure 5 Polarizing microscope photographs of the FLC alignment: (a) and (b) show those of bent and nonbent states, respectively

We believe that the high bending tolerance of the device is attributable to the adhesive polymer walls which divide the FLC layer into small equal parts in the device plane. If exfoliation of the polymer walls from the substrates does not occur, this can prevent the flow of the FLC across the polymer walls. In addition, the polymer walls can deconcentrate the bending strain in the plane of the device. That is, the difference in length, which is caused by expansion and contraction of the substrates, between the outer and inner planes of the FLC layer, is also divided into every FLC area surrounded by polymer walls. We estimated the influence of bending on the FLC molecular alignment by calculating the difference (ΔL) between the outer (X) and inner (Y) length of the FLC layer in an area surrounded by polymer wall, as shown in Fig.6 [9].

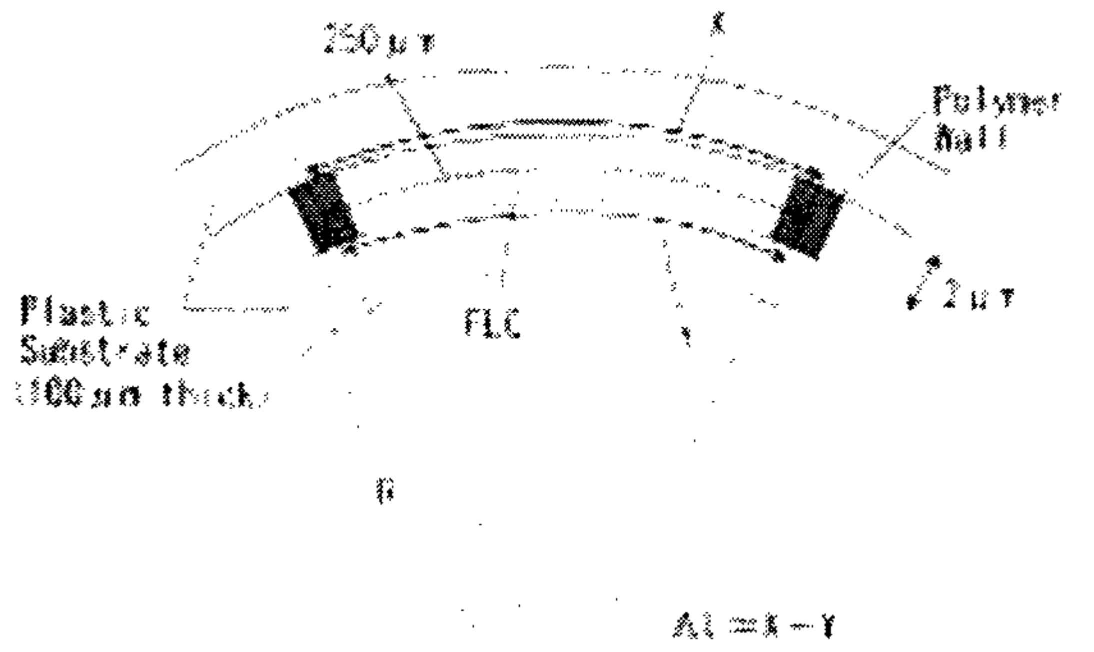

Figure 6 Calculation method for the length between the outer and inner planes of the FLC layer caused by bending

ΔL can be obtained by

$$\Delta L\,[\mathrm{nm}] = \frac{500}{R\,[\mathrm{mm}]} \qquad (1)$$

When R is 7mm, ΔL is only about 70nm, which is very small compared to the interval between the polymer walls (250μm). This means that the difference in length between the two sides of the FLC layer is only one FLC molecular length when a few thousand molecules are aligned in the direction of the long axis of the molecule. We therefore think that the relaxation of bending is performed by a slight bending deformation of the smectic layer structure of the FLC alignment. This suggests that the device can be bent in a smaller radius by using more extensible substrates.

5. Electro-optic properties

We fabricated a 100mm×100mm device using 100-μm-thick substrates, which was sandwiched between two 200-μm-thick crossed polarizers. Though the bending tolerance of the device is mainly limited by the flexibility of the polarizers, the device could be bent to a radius of 15mm without any disorder of the FLC alignment. If the polarizing thin films are directly formed on the substrates by coating [10], the influence of the polarizers can be ignored. Figure 7 shows the fabricated device without polarizers.

Figure 7 Appearance of the fabricated FLC device

Figure 8 shows micrographs of a device with polarizers bent in a radius of 15mm under different applied voltages. The μm-sized FLC switching domains expand with an increase in applied voltage, and hence, the device exhibits grayscale capability, even when it is bent in such a small radius.

The electro-optic response to an applied pulsed voltage was also measured in the device bent with a radius of 15mm. The response time and contrast ratio of a bent device were the same as those obtained in the same device without bending. This is because the deformation of the smectic layer structure is extremely small even when the device is bent in such a small radius.

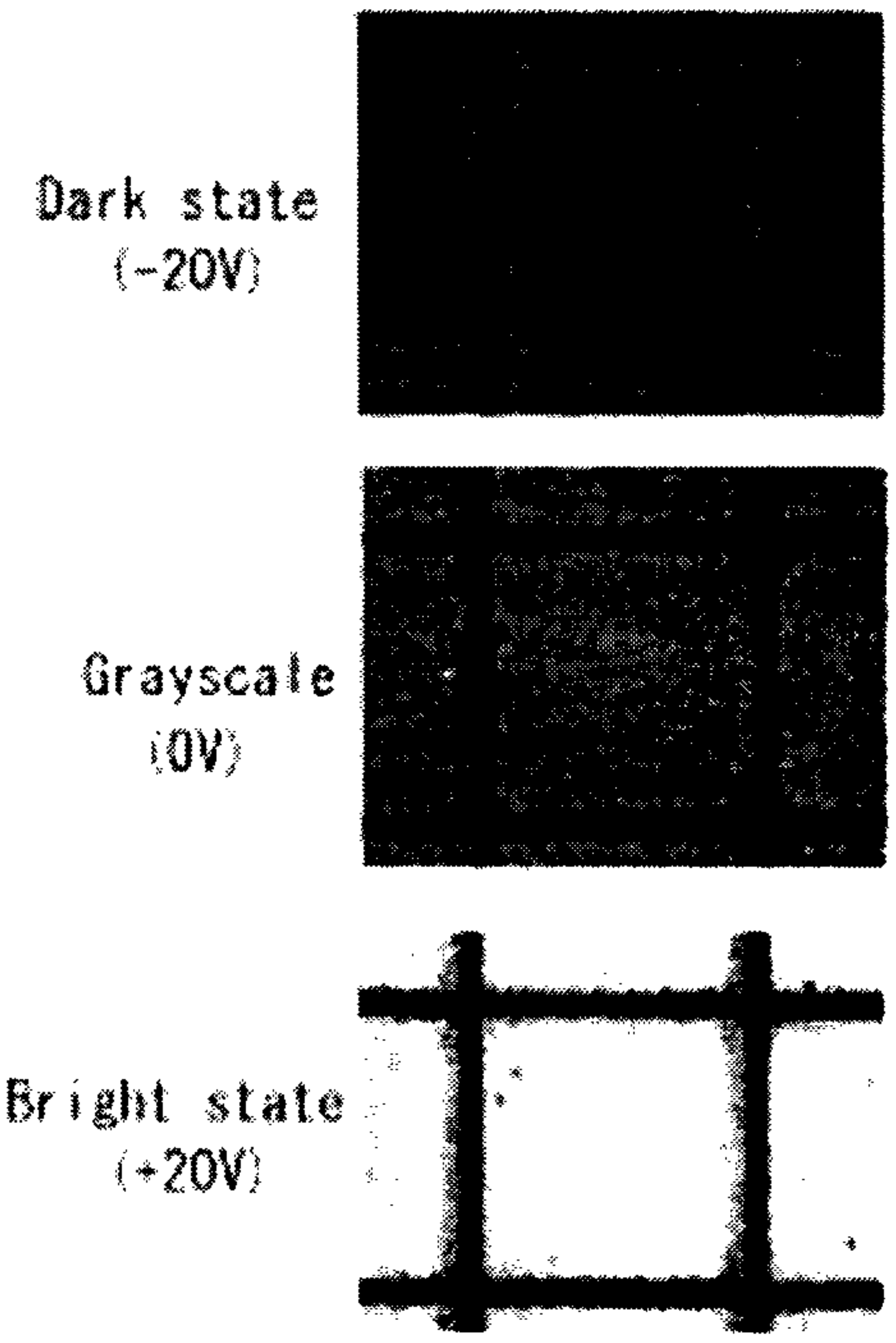

Figure 8 Polarizing microscope photographs of the FLC device bent to a radius of 15mm under different applied voltages

6. Rollable Display

The FLC device using thin plastic substrates supported by polymer walls is lightweight, thin and flexible, and hence, it can be applicable to future "rollable displays". Figure 9 shows a rolled device with patterned ITO electrodes. The device was sandwiched between two polarizers with a thin light diffusion film located on the inner polarizer. The radius of curvature of the bent device was about 20mm.

When the diffusion film was illuminated with white light, the light through the film was scattered and was used as a backlight. The light transmitted through the device could be modulated by an applied voltage. This device demonstrates a roll-up display with uniform grayscale capability.

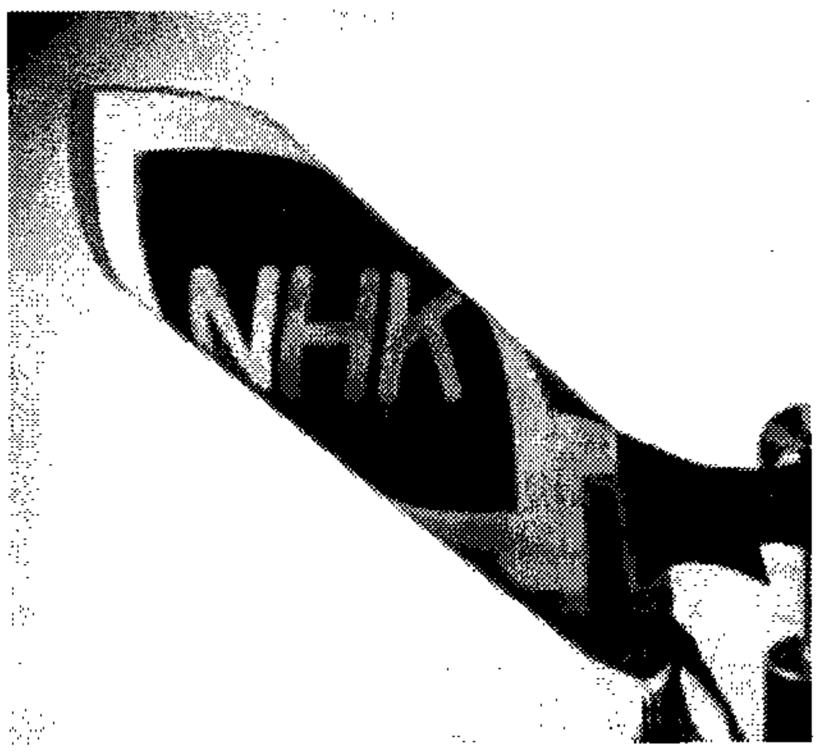

Figure 9 Display operation of a roll-up FLC device driven with patterned ITO electrodes

7. Conclusions

We developed a flexible FLC device using thin plastic substrates fixed by polymer walls and networks. The device using 100-µm-thick substrates could be bent in a radius of 7mm without disorder of the FLC alignment. A rolled device sandwiched between two polarizers exhibited uniform light modulation with grayscale display operation.

In future work, more extensible substrates and polarizers with high flexibility need to be applied to the device in order to obtain more bending tolerance. We also need to advance the research on improvement of the contrast ratio and active driving methods [11].

8. References

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