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High-efficiency multistable switchable glazing using smectic A liquid crystals

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ABSTRACT

Presently, nematic polymer dispersed liquid crystals (PDLCs) that are used in switchable glazing technology require constant power to operate and, moreover, exhibit unwanted haze at wide viewing angles. In this paper, a novel switchable glazing technology, based around a bistable electro-optic effect in the Smectic A liquid crystal phase, is described which does not require constant power to operate or exhibit haze. The application of a low-frequency (100 Hz) voltage induces an optically opaque state due to the motion of ionic material whereas the application of a higher frequency AC (1 kHz) voltage induces a haze-free clear state. Multistable (greyscale) operation is possible through the application of intermediate frequencies or voltages; the threshold voltages of the effect were found to range from 36 to 66 V rms. Any voltage-induced state is preserved indefinitely after removal of the voltage leading to low power consumption.

1. Introduction

Two main technologies exist for the control of sunlight and switchable windows ("smart" windows), namely electrochromic-type devices and polymer dispersed liquid crystals (PDLCs) [1–3]. In a PDLC device, liquid crystal droplets are suspended in a polymer matrix sandwiched between transparent conductive glass substrates. In the "Off" state, the random orientation of the liquid crystal within the droplet results in an opaque state; the application of a sufficiently high voltage causes the liquid crystal material to align with the field, reducing the refractive index contrast between the polymer and the liquid crystal, and turns the film clear. Typical operating voltages are in the range 20–100 V rms to maintain the clear state of the device [5]. PDLC films have several undesirable features, however, the device requires a continuous voltage to be applied to remain clear and exhibits scattering ("haze") at wider viewing angles in this clear state. In this paper, we consider an alternative liquid crystal device based upon the Smectic A phase which offers significant advantages over the PDLC; namely multistable operation and a clear state at all viewing angles.

Liquid crystal materials possess different degrees of ordering intermediate between isotropic (liquid) and crystalline states [4]. Practically, to-date, nematic liquid crystals have received the greatest commercial attention (e.g. TFT laptop screens); this class of liquid crystal possesses orientational order, such that the long axes of the molecules have a preferential alignment, but no positional order. The preferential axis of alignment is termed as the director. Other liquid crystal phases exist in which the orientational order is accompanied by different degrees of positional ordering. For example, in the smectic A phase the orientational ordering is accompanied by a layer-like correlation of the constituent molecules.

In this paper, we examine an alternative electro-optic effect that is observed in the smectic A phase [6]. A schematic of the device operation is shown in Fig. 1: upon application of a low-frequency voltage (typically less than 100 Hz), the device becomes opaque due to the motion of ionic additives through the layered smectic A structure. This generates a highly scattering focal conic texture with typical feature size of the order of ~1 μm (herein this is referred to as the "write" state). Application of a frequency beyond a critical value (e.g. 300 Hz–1 kHz) restricts the ionic motion and the device becomes clear as the long axes of the liquid crystal molecules rotate to dielectrically align with the field (herein this is referred to as the "erase" state). Both modes are preserved after removal of the voltage and, owing to the higher viscosity of the smectic A phase, the induced textures can be stored indefinitely. Microphotographs of the induced textures are presented in Fig. 2. The scattering texture emerges from the cell electrodes, and from scattering centres in the bulk of the cell.

Theoretical descriptions of the device have been proposed so as to provide insight as to the relationships between the thresholds and the dielectric and conductive properties of the liquid crystal. For the "write" state the threshold depends upon the thickness of the layer, d, the dielectric permittivity parallel to the director, $\varepsilon_{\parallel}$, and the conductivity ratio, where the subscripts refer to parallel

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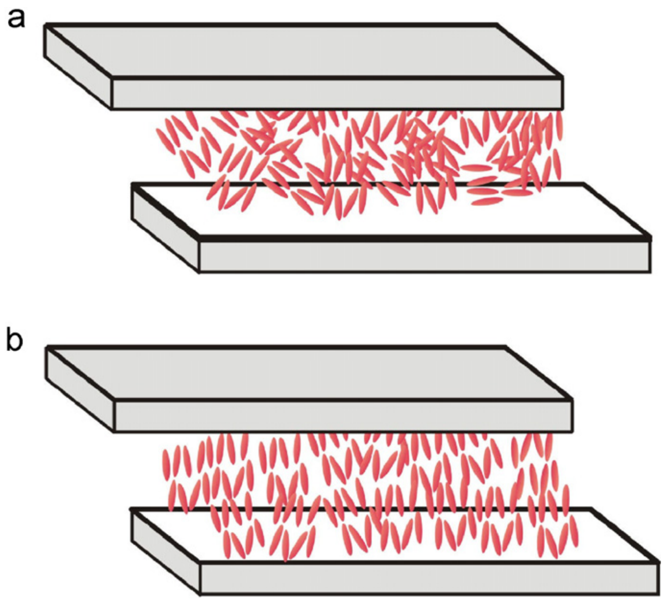

Fig. 1. Schematic of device operation, (a) highly scattering focal conic texture due to the motion of charged impurities at lower AC frequencies (e.g. 100 Hz) and (b) optically clear state induced by dielectric reorientation of the liquid crystal at higher AC frequencies (e.g. 1 kHz).

and perpendicular to the director. Explicitly, this is given by

$$V^2_{write} \propto \frac{d}{\varepsilon_{||}(1-\sigma_{||}/\sigma_{\perp})}, \quad (1)$$

whereby the voltage, V_{write}, corresponds to the highly scattering texture. On the other hand, for the "erase" state, the threshold depends upon the dielectric anisotropy, $\Delta\varepsilon$ ($=\varepsilon_{\parallel}-\varepsilon_{\perp}$, and the thickness of the layer [7]. This is written as

$$V^2_{erase} \propto \frac{d}{\Delta\varepsilon}. \quad (2)$$

where by V_{erase} refers to the scattering to clear transition.

The described electro-optic effect offers increased electro-optic performance compared to conventional PDLCs because the induced modes are preserved after removal of the applied voltage thus reducing power consumption significantly in the clear state. Furthermore, the optical performance is superior—with no viewing angle dependent haze.

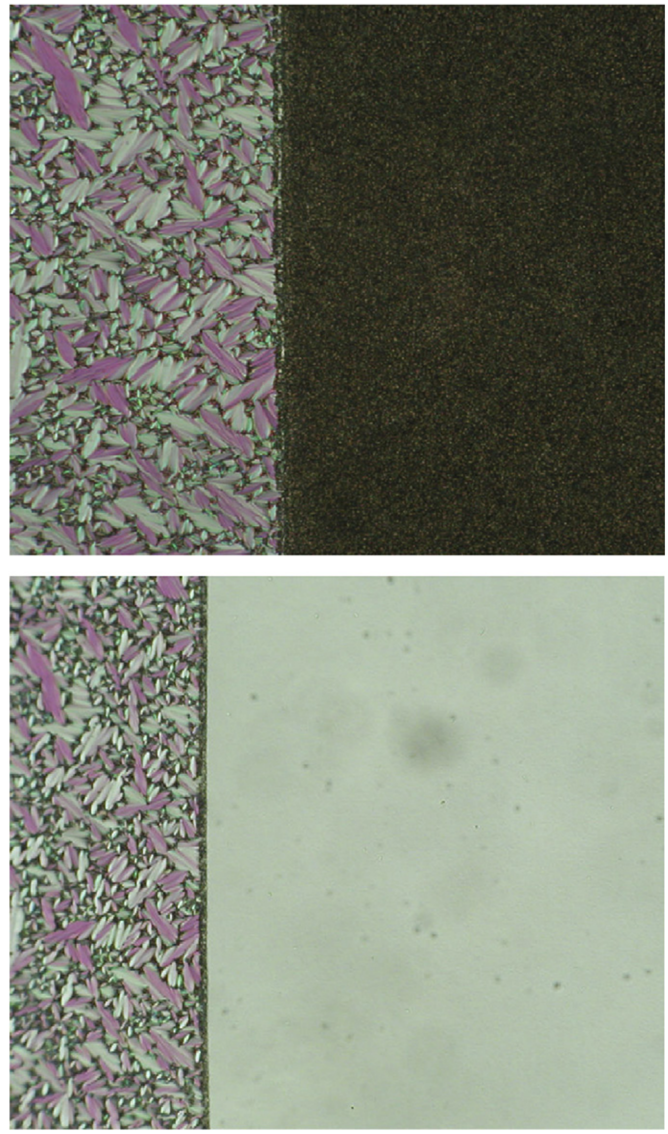

Fig. 2. (color online only) Optical textures of the stored write (left) and erase modes (right). The active (electrode) area is to the right of the pictures. The distance across the pictures is approximately 500 μm.

2. Materials

The smectic A material used in the investigation is an in-house proprietary mixture of organosiloxane liquid crystals optimised for low operating voltages [8–10]. Organosiloxane materials readily exhibit wide temperature range smectic A phases extending below room temperature. These materials consist of three chemically distinct parts: siloxane moiety, oil-like alkyl chains and aromatic core. The origin of the unusual Smectic A behaviour is in the separation of these components into distinct sub-layers within the overall layered structure [9]. A schematic of this principle is presented in Fig. 3.

The mesomorphic behaviour of the material used in the investigation is as follows: crystal to smectic A (<0 °C), smectic A to nematic phase (74 °C) and smectic A to isotropic phase (78 °C). The mixture is designated as Sample A. The dielectric and conductivity properties, which control the threshold and the operating voltages (Eqs. (1) and (2)) for Sample A were $\Delta\varepsilon$~7.2 and $\sigma_{\parallel}/\sigma_{\perp}$~0.58, measured at 10 kHz and 100 Hz, respectively. To facilitate the scattering process an ionic additive cetyltrimethy-

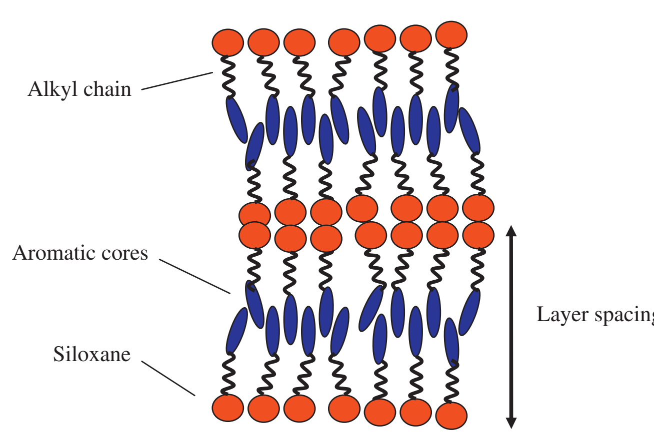

Fig. 3. Schematic representation of the molecular arrangement in organosiloxane Smectic A liquid crystals.