New Functional Polymers for Liquid Crystal Displays Review of Some Recent Developments

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SUMMARY: Polymeric materials play an important role in the construction and performance of liquid crystal displays. New functional polymers are developed to improve the displays on brightness, power efficiency and viewing angle performance. Polymer films with a controlled molecular structure and architecture provide new polarization optics to convert non-polarized light into polarized light with higher efficiency than the traditional polarizers based on stretched iodine doped poly(vinyl alcohol). Other films provide a polarization compensation function to maintain an angular invariant net optical retardation of the display device and therewith a better contrast to wider viewing angles. Color generation by non-absorbing methods is believed to improve on the display brightness. Special control of the liquid crystal alignment by photo-sensitive orientation layers, polymer protrusions or photo-formed polymer walls provide multiple director patterns within a single pixel to average out angular LC effects.

Introduction

Flat panel liquid crystal displays (LCD's) are presently widely accepted as interface between man and machine. Their complexity range from simple segment-wise addressed watch- or calculator displays to ultra-high resolution computer screens. From the first twisted-nematic (TN) displays, as discovered by Schadt and Helfrich[1], to the multi-pixelated vertically aligned nematic (VAN) displays as proposed by Takeda et al.[2], the display performance, as manifests itself in contrast, color saturation, viewing angle, switching rate, luminance, power consumption, etc., has come a long way.

Functional polymer materials have played important role in bringing the product to the state where we are now and are expected to contribute further to future improvements. Especially in an age where each new generation of electronics products is smaller and more portable than the last, the aim for manufacturers is to find lightweight robust displays with low power requirements.

 CCC 1022-1360/00/$ 17.50+.50/0

Apart from the glass substrates, the indium-tinoxide electrodes and the active matrix TFT's, a current LCD is built from numerous polymeric materials, mostly in the form of thin films. Table 1 summarizes the polymers that are found in present display designs. Of course the most essential layer is that of the electro-optical switch, being the still low molar mass LC. But also here there are many developments to stabilize the molecular organization in this layer by a polymeric network or to replace it by a fully polymerized LC film thus creating a solid state electro-optical switch that improves the display especially on manufacturing concepts. And a step towards an all-plastic display could be to replace the glass substrates by stable plastics[3,4]. Or even, but somewhat further in the future, one might think of building the AM logic from polymeric semiconductors and the electrodes from polymeric conductors.

Table 1. Examples of Polymeric Materials in Current LCD's

Function	**Current materials selection**
polarizer films	stretched polyvinyl alcohol-iodine protected by cellulose triacetate
polarization recycling films	cholesteric liquid crystalline acrylates, polyesters
liquid crystal orientation layer	buffed polyimide
color filter	pigmented photo-setting acrylates
black matrix	e.g. pigmented photo-setting acrylates
planarization	photo-setting acrylates
compensation films to improve on viewing angle performance in TN	tilted photo-setting liquid crystalline acrylates (discotic- and calamitic nematics)
compensation films to improve on color performance in STN	stretched polycarbonate
cell adhesives / seal fill opening	epoxies / thiolenes
cell spacer spheres	e.g. poly(styrene-co-divinylbenzene)
backlight waveguide	acrylates, polycarbonate
diffuser films	e.g. cellulose
light collimating films	embossed/extruded polycarbonate or acrylate films with surface profile

New developments aiming improved efficiencies of the LCD's are concentrating on the polarizers and color filters, being the components that waste most of the light generated by the backlight. Non-light-absorbing counterparts of the present polarizers and color filters will provide a tremendous improvement on luminance and power efficiency in the near future.

Other development are aiming to attack the notorious bad viewing angle of the LCD's by introducing dedicated compensation films, new display effects, sub-divided pixels, or combinations thereof. Also here polymers play an essential role either in controlling the state of polarization of the transmitted light or by providing new means to direct the LC molecules on a sub-pixel level.

Functional polymers for brighter displays

Table 2 shows the transmission characteristics of the various components of a display that the light generated by the lamp or LED passes on its way to the viewer. The numbers may differ somewhat for the different types of LCD's but the general observation is that of the light generated by the lamp system only 3 to 10% is used. The result is that an average, backlit LCD has a maximum brightness of 200 Cd/m^2 whereas an average CRT provides 500 Cd/m^2.

Table 2. Efficiency of display components

Display element	**Efficiency (%)**	
	individual	**cumulative**
lamp reflector + in-coupling	80	80
backlight waveguide + diffuser	80	64
back polarizer	44	28
display aperture	70	20
color filters	28	6
front polar	95	5

A major energy consumer in standard LCD's is the polarizer. Traditionally it is composed of a stretched poly(vinyl alcohol) film doped with iodine crystals or dichroic organic dyes. Polarization of light is obtained by preferential absorption of light with its E-vector parallel to the orientation axis. Intrinsically, these leads to a transmission efficiency <50%. However, in the recent past several elegant solutions have been found to circumvent this yield problem.

One way of improving the yield of producing polarized light is based on the so-called recycling principle. The principle is schematically shown in Figure 1. If polarized light is produced not by absorption but by means of reflection, light of the wrong polarization is re-directed into the backlight of the display. Usually the backlight consists of a sidelit imprinted

PMMA waveguide with a diffuse reflector at the backside and a transmissive diffuser film at the side towards the LCD panel. The re-directed light of wrong polarization becomes depolarized by the diffuser films and is for a large part reflected again towards the LCD panel again. In a repetitive process the reflective polarizer again selects the right and rejects the wrong polarization such that, depending on the efficiency of the optical design of the backlight, ultimately the yield of polarized light can become close to 80%.

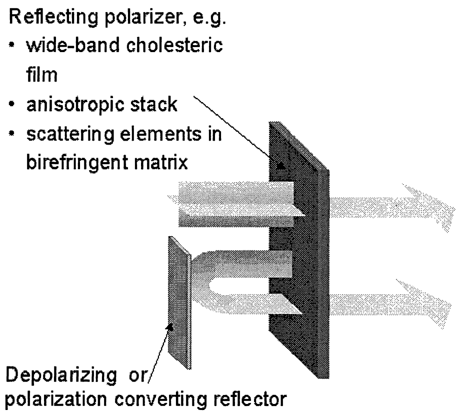

Fig. 1: Schematic representation of the recycling principle.

Basically three principles have been worked out to produce polymeric reflective polarizer films. The first one is based on so-called cholesteric networks[5,6]. The principle is shown in Figure 2. A thin coating of a chiral-nematic acrylate monomer is applied on a birefringence-free substrate and cured. The molecular organization within the acrylate film separates light on its state of circular polarization. To get sufficient bandwidth the pitch of the molecular helix is subjected to a gradient over the film thickness. In order to produce linearly polarized light a quarterwave retardation foil needs to be laminated although very recently cholesteric polarizers are proposed with a built-in quarterwave retardation function[7].

An alternative reflective polarizer is based on a stack of alternating birefringent layers optimized such that one state of linear polarization experience no transition in refractive index and is transmitted and the other polarization is reflected under the Bragg's conditions[8]. A similar effect, but now based on diffuse reflection rather than on specular reflection, is obtained when a blend of an highly birefringent polymer, e.g. poly(ethylene-2,6-naphtylene

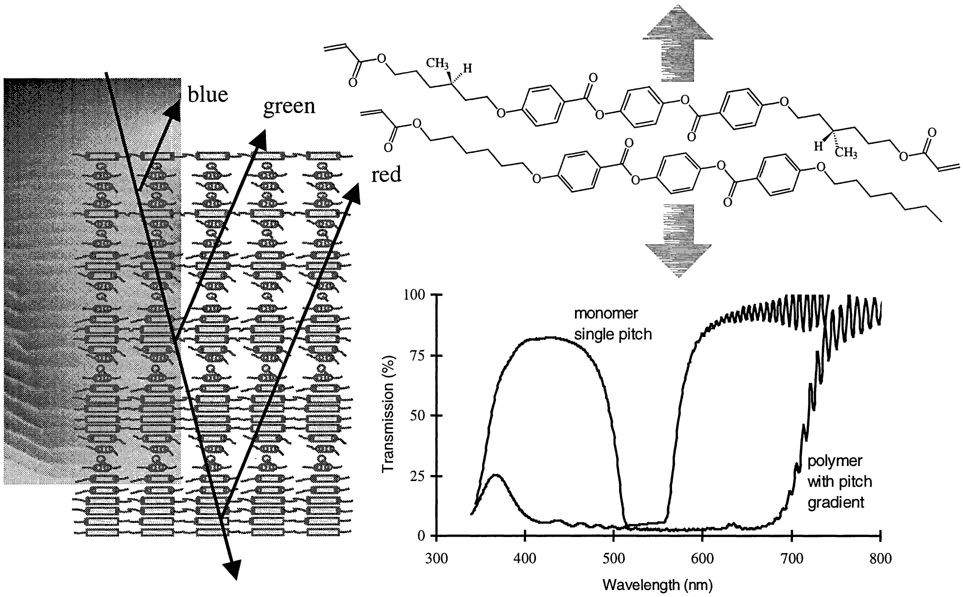

Fig. 2: Helix gradient provides polarized reflection over entire visible wavelength region. The pitch gradient established by photo-induced diffusion of the chiral-nematic diacrylate and the nematic monoacrylate is shown schematically and by the SEM picture of a fractured cross-section of the film.

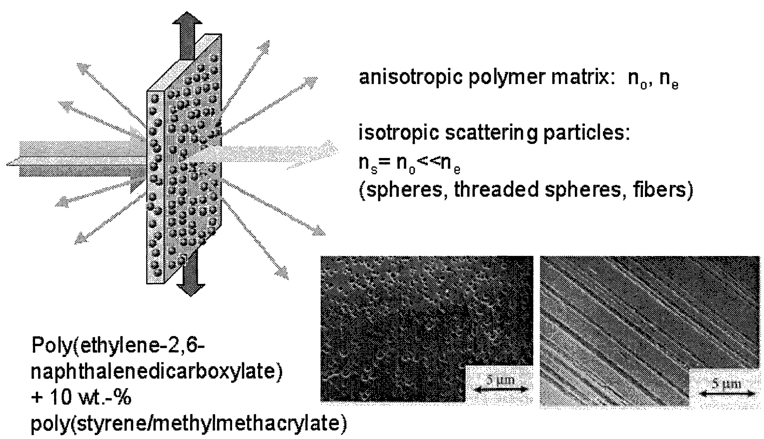

Fig. 3: Scattering of polarized light in a stretched polyester film provided with isotropic, index-matched particles. The SEM pictures show cross-section of the films into the direction perpendicular (left) and parallel (right) to the stretching direction[9,10].

dicarboxylate), and optically-isotropic particles are extruded into a thin film en subsequently stretched to a state in which the ordinary refractive index of the PEN matches the index of the particles[9,10]. Figure 3 shows the principle as well as SEM picture on the shape and distribution of the particles. These scattering polarizers have the benefit that they can be made from commodity plastics and by current and cheap manufacturing technologies.

Rather than recycling wrongly-polarized light, another way to improve the backlight efficiency is by using the direct generation of polarized light using dichroic photoluminescence (Figure 4)[11]. Stretched polymer films are provided with a combination of an isotropic sensitizer (DMC) and an aligned dichroic fluorophore (PPE). The sensitizer absorbs the unpolarized light, as for instance generated from a gas discharge lamp, and transfers its excited state energy to the fluorophore. The latter emit polarized light with the E-field vector parallel to the average orientation of the transition moments.

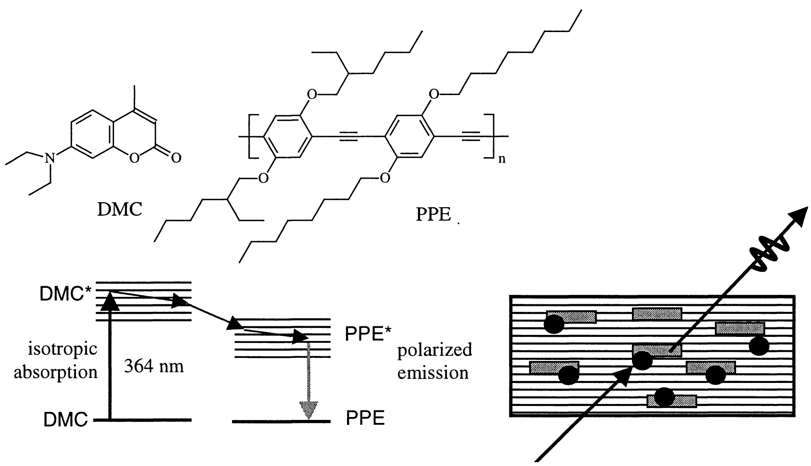

Fig. 4: Ball and stick model for the Förster/Dexter energy transfer from unpolarized UV light to polarized visible light. The isotropic DMC molecule transfer its excited state energy to the anisotropic PPE molecules that emits polarized light[11].

Another major energy consumer in a display is the color filter. White light produced by for instance the gas discharge lamp is converted into R, G and B by removal of the remaining part spectrum, reducing the efficiency of this component to less than 30%. An enormous improvement in the efficiency can be obtained by methods that are basically the same as those described for the generation of polarized light. The recycling principle can be used by designing color filters based on reflection rather than on absorption. Again polymeric cholesteric materials prove to be very useful in achieving this [12,13]. In the case where single

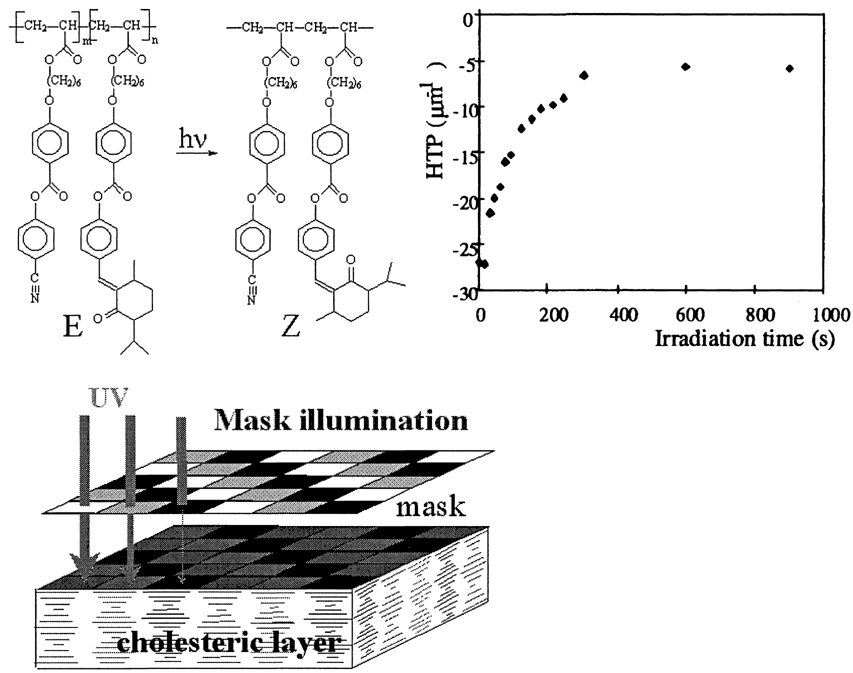

Fig. 5: The E-Z isomerization reaction that leads to adjustment of the helical twisting power (HTP) and the technology to produce red, green and blue reflecting color filters in a single exposure step[12,13].

layer R,G,B or C,M,Y color reflectors are used, as demonstrated in Figure 5, the improved efficiency is accompanied by a reduced number of processing steps in display manufacturing.

Colors can also be generated directly from UV or blue light by using photoluminescent color filters[14,15]. Recently, much progress has been made with classical inorganic phosphor materials as optimized for plasma displays or fluorescent lamps. However, also here a bright future is foreseen for organic materials because of their ease of processing and transparency, especially if some of optical functions as described above can be combined in single layers.

Functional polymers for better viewing angle

A major imperfection of LCD's is their limited viewing angle in comparison to cathode ray tubes. The origin can be found in the angular dependence of the optical retardation of the

LC's. However, presently several functional-polymer-based solutions, based have been found to improve LCD's on eye-catching property.

A relatively straight-forward, yet difficult to realize, solution is to add phase compensation films in which the molecular organization mimics that of the liquid crystal in the most sensitive state, e.g. the (partly) addressed state of a so-called normally white TN-LCD, in a complementary manner (Figures 6 and 7). Several types of these so-called wide-viewing-angle foils have been demonstrated. For instance discotic polymeric network films with a tilted optical axis, applied between the LCD cell and the polarizer, gave an enormous improvement on the angular dependence of contrast and grey scale inversion[16]. Comparable improvements of the optical performance are obtained from crossed tilted calamitic liquid crystalline networks[17] and volume holograms with a tilted optical axis based on form birefringence[18].

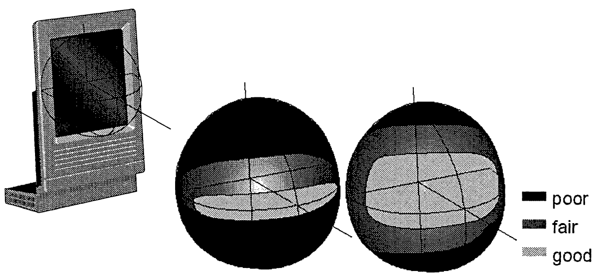

Fig 6: Improved viewing angle performance of an foil compensated LCD. The left hemisphere provides the spatial viewing angle of a non-compensated TN LCD, the right hemisphere that of a LCD compensated by two tilted calamitic foil compensators.

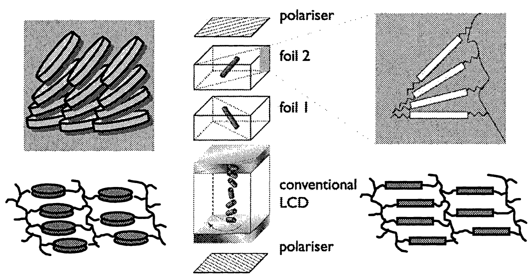

Fig. 7: Wide viewing angle films based on tilted discotic networks (left) or tilted calamitic nematic liquid-crystalline networks. The central part shows an arrangement in which two differently tilted films are brought on top of the display to compensate for the angular dependent retardation of the TN-LCD in the addressed state[16,17].

Another improvement stems from the control over the molecular alignment of the LC's. In most displays the orientation layer, normally a buffed thin polyimide film, imposes the direction of the LC alignment. The unidirectionally buffing process implies a uniform alignment over the total surface of a picture element (pixel). Further improvement of the viewing angle is now obtained by combining differently oriented domains in each pixel[19]. Photosensitive polymers provide areas of different alignment by patterned exposure to polarized UV light. Only the dichroic chromophores with their transition moment parallel to the E-vector of the light undergo a reaction, often a cycloaddition[20,21], an EZ isomerization[22], or photodegradation[23], thus creating the conformational rearrangement that aligns the LC's. Figure 8 demonstrates that accurate patterns can be obtained by this method.

Besides in TN-LCD's, this multi-domain pixelation is also successfully utilized in the VAN displays. LC's with negative dielectric anisotropy are vertically aligned thus providing a superior and easy-to-compensate black state. When addressed by an electrical field the LC's switch to planar but by smartly applied discontinuities, described as protrusions (Figure 9), in the photopatterned orientation layer they are forced to four discrete directions within each pixel thus averaging birefringence effects over all directions[2].

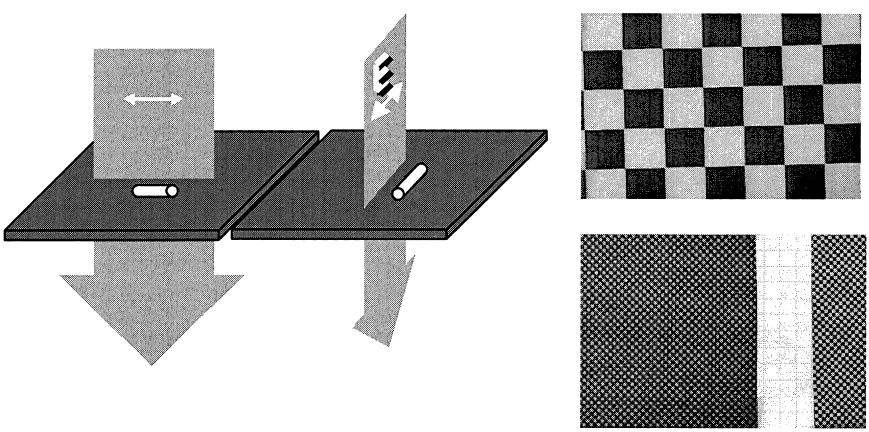

Fig: 8: Masked exposure of a photo-alignment layer with polarized light followed by a flush exposure of oppositely polarized light at one side of the liquid crystal cell and just linear flush exposure at the other side of the cell provides alternating uniaxially aligned nematic layers and twisted-nematic layer. The polarized microscopy pictures taken between crossed polars show the line definition of differently oriented E7 liquid crystal patterns obtained by coumarin-based alignment layers[21].

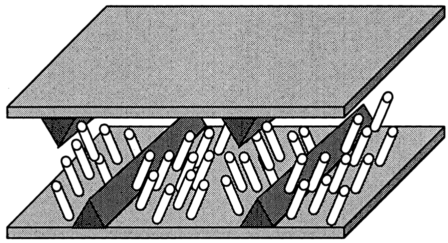

Fig. 9: Director modulations by protrusion applied in substrates that are subsequently coated with a homeotropic orientation layer. The director fluctuations in the field-off state convert to a pronounced multi-domain planar molecular organization when the nematic negative dielectric anisotropy liquid crystal is switched by an electrical field, thus improving on the viewing angle[23].

Polymer stabilized LC effects

Apart from LC orientation induced at the rubbed or photo-aligned polymeric interface near the electrodes, polymers polymerized as separate phase in the bulk LC may command the molecular order to a very large extent. Polymer dispersed liquid crystals[24], LC gels[25,26], polymer filled nematics[27], polymer stabilized cholesterics, etc. have been found to produce displays based on diffuse or specular reflection that operate basically without the use of polarizers. Very often these display approaches provide easy-to-manufacture, cheap and robust electro-optical switches which, because of their optical performance, can be found in hand-held applications as watches and telephones.

A special type of polymer stabilized LC orientation is the axially symmetric aligned microcell (ASM) mode that is presently proposed by Sharp, Sony and Philips for high-end video-on-the-wall plasma activated liquid crystal televisions with wide viewing angle[28]. The special feature of this product is that it combines several of the features that have been discussed above. Vertically aligned LC's are brought in pixel-sized cells constructed of in-situ formed polymeric walls. Upon addressing they switch to a planar state into a axially symmetric way thus providing the ideal multi-domain structure with only a single contrast reducing disclination point rather that lines at the domain boundaries. Instead of 2 or 4 domains separated by disinclination lines, we have now infinite molecular directions with only 1 disclination point. The result is a good viewing angle, a high contrast and still a high aperture as the polymer walls can be accurately positioned at the pixel edges. A process to form the polymer walls is to dissolve polyfunctional acrylate monomers together with a minor amount of photoinitiator in the liquid crystal and have them polymerized at the desired position by masked exposure to UV light.

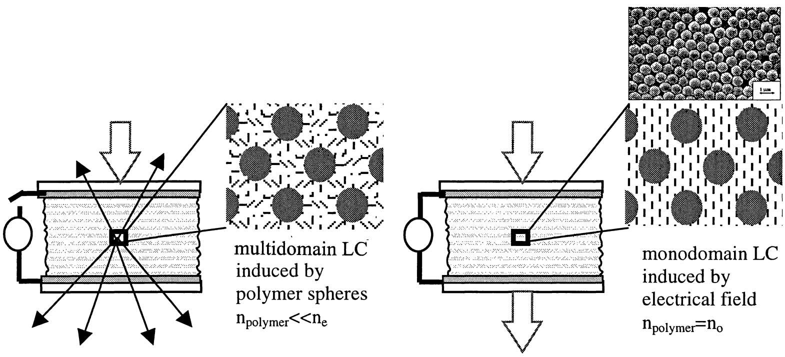

Fig. 10: Schematic presentation of a polymer filled nematic liquid crystal cell in the unaddressed and the addressed state[27]. The SEM photograph shows 800 µm spheres used for this application.

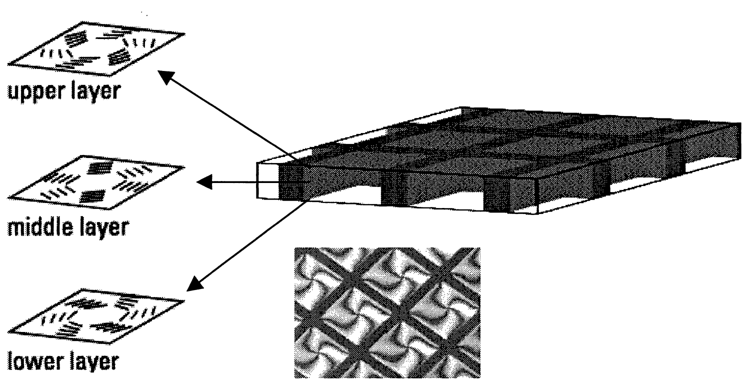

Fig. 11: ASM polymer walls and the microcell-controlled orientation of the liquid crystal in the addressed state. The photograph shows the texture of the pixels as observed by polarizing microscopy, indicating the reproducibility of the molecular organization over all pixels[28].

Conclusions

Present liquid crystal displays owe their performance largely to the presence of specially designed polymers. Examples are light management films in backlights, orientation layers to control liquid crystal alignment and lithographic color filter materials to make R,G,B color displays. New materials that are currently under development are expected to enhance the display enhancement even more on brightness, power efficiency and viewing angle performance. Examples are new optical films that provide unique functions in polarization optics and new alignment layers that control multiple liquid crystal orientation within a single pixel.

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