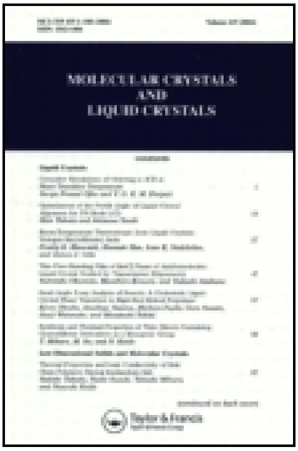

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Recent Advances in LPP-Photoalignment of Liquid Crystals Applied to the Phase Retarder Image of Alfred Saupe

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By means of photo alignment and simultaneous cross-linking of linearly photopolymerizable (LPP)-polymers we have recently succeeded in generating uniaxial planar alignment in adjacent liquid crystal polymer (LCP)-films deposited on *single* LPP-substrates. This renders the design of optically anisotropic and photopatternable hybrid layers of LPP- and LCP-films on single substrates feasible, leading to high resolution optical phase retarder LPP images. The new technology opens-up the possibility to generate and photopattern polarization interference color filters, linear polarizers and color compensators integrated directly on liquid crystal display substrates. Recent progress allows photogenerating an optical retarder image of Alfred Saupe in honor of his seventies birthday.

Keywords: Photoalignment; phase retarder; Alfred Saupe

Until recently exclusively unpolarized uv-light was used for crosslinking photopolymers. Because of the isotropic spacial distribution of the photoreactive moities in precursor photo-polymers and due to the isotropic nature of the electro-magnetic field of unpolarized light interacting with the prepolymer molecules, conventional photopolymerization leads to optically isotropic polymer films.

In search for non-mechanical aligning technologies for monomeric liquid crystals we have shown that anisotropic photopolymerization can be achieved by cross-linking side chains of poly(vinyl 4-methoxycinnamate) [PVMC] precursor photopolymers not with unpolarized, but with linearly polarized uv-light. As a consequence initially isotropic PVMC-films were converted into sterically and optically anisotropic films. [1]) This mechanism, which we denominated linearly photopolymerizable (LPP)-process, was shown to be due to the ability of linearly polarized light to simultaneously *align* and

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cross-link the long molecular axes of PVMC-side chain molecules uniaxially in a direction determined by the direction of linear polarization. Moreover, LPP-film surfaces were shown to induce uniaxial planar alignment in monomeric liquid crystal layers confined between the two substrates of a liquid crystal display. [1]) The simultaneous generation of intermolecular anisotropy and cross-linkage distinguishes the LPP-concept from the photoaligned guest-host photopolymers of Gibbons *et al.* [2]) where intense linearly polarized laser light is used to induce uniaxial alignment of dichroic guestmolecules imbedded in a photopolymer host matrix. Since the guest-host process does not chemically fix the orientation of the dichroic dyes in the host, the alignment is reversible.

We have shown that the LPP-technology is able to generate planar, high-resolution azimuthal liquid crystal aligning patterns in liquid crystal displays (LCDs) as well as optically weakly birefringent patterns with azimuthally adjustable slow optical axes. [1]) However, because of the so far weak optical anisotropy $\Delta n = (n_e - n_0) \simeq 0.005$ of LPP-films, the optical retardation required for realizing efficient optical retarders, polarization converters and polarization interference filters is not sufficient. Moreover, because the slow optical axis of the refractive index ellipsoid of an LPP-pattern coincides inevitably with its direction of LC-alignment, [1]) aligning and retarder functions of photo-aligned films cannot independently be generated and controlled.

Recently we have demonstrated that photoaligned LPP-films not only align monomeric liquid crystals confined between two LPP-coated substrates but that they also generate uniaxial planar alignment in adjacent liquid crystal prepolymer (LCP)-layers deposited on *single* LPP-substrates [4, 5]). Moreover, we found that the LCP-alignment is preserved during subsequent cross-linking of LCP-prepolymers up to layer thicknesses of several micrometers. New LPP-materials withstanding high processing temperatures were developed which enable the integration of optical retarder and aligning functions with arbitrary angles between their respective axes [4]. In the following these findings are reviewed and shown to render photo-patterning of complex LPP-and LCP-layers on single substrates feasible. The interesting potential of photopatterned LPP-retarders is demonstrated by the complex, parallel processed optical phase retarder image made of Al Saupe. The image is generated by almost conventional photolithographic means.

Figure 1 schematically illustrates our LPP-concept for an optically patterned phase retarder configuration with integrated aligning and retarder properties [4, 5]). The LPP-retarder consists of two picture elements (pixels) with two different slow optical axes n_{e1} and n_{e2} on a *single* glass substrate S.

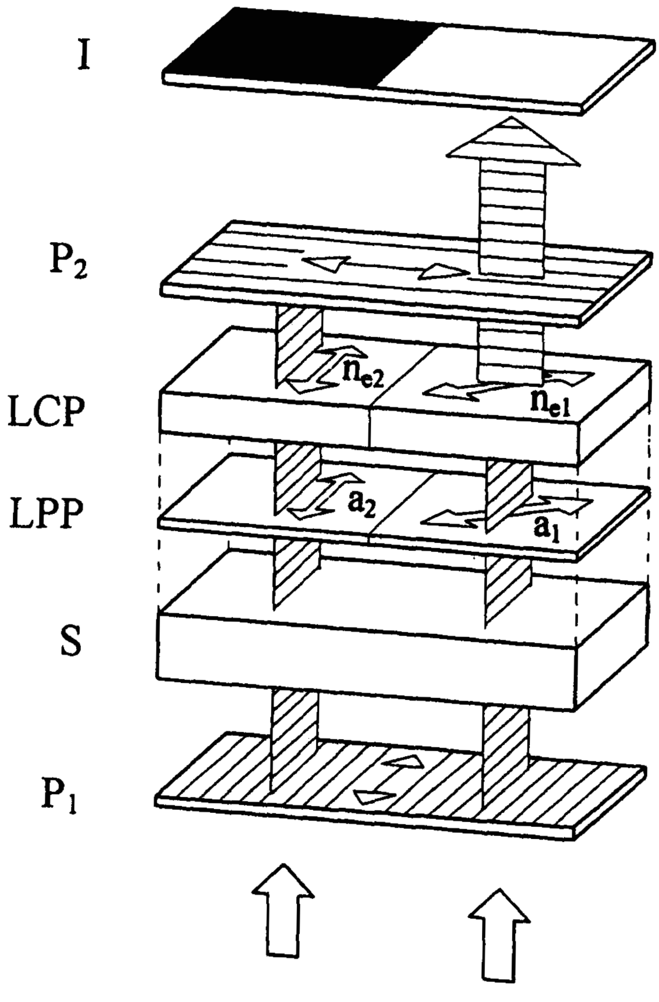
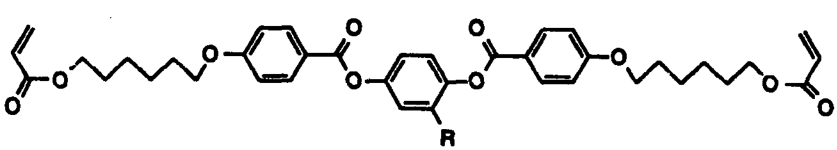


FIGURE 1 Optically patterned HLPP-retarder configuration on a single glass substrate S between external crossed polarizers P_1, P_2. The LC-aligning directions of the 120nm thick LPP-film a_1, a_2 parallel the slow optical axes n_{e1}, n_{e2} of the 2 μm thick pixellated LCP-film on top; optical retardation δ(LCP) = 230 nm.

The function of the photopatterned LPP-layer is to align the LCP-layer on top. In Figure 1 the linear polarizers P_1, P_2 visualizing the phase retarder image are external; however, they can also be integrated. As described earlier [1,4]) the different LPP-aligning directions a_1 and a_2 were achieved by first linearly photopolymerizing the LPP-coated glass substrate via a photo mask with linearly polarized uv-light of a 200 W mercury lamp along direction a_1. In a second step the photo mask was removed, the direction of linear uv-polarization rotated by 45°, thus photo cross-linking and aligning pixel 2 along direction a_2. Next, a nematic precursor LCP-film was spin-coated on top of the LPP-layer. Upon contacting the LPP-substrate, the planar uniaxial LPP-alignment directions a_1 and a_2 became transferred into the precursor LCP-film, turning the LCP-film optically anisotropic with its slow optical axes n_{e1} and n_{e2} aligned parallel to a_1 and a_2. The LCP-film thickness d was chosen such that an optical retardation $\delta(\text{LCP}) = \Delta n \cdot d = (n_e\text{-}n_0) \cdot d = 230$ nm results, where Δn is the birefringence of the LCP-film. Finally, the optical pattern of the LPP-aligned precursor LCP-film was transferred into the solid state by cross-linking the LCP-film with unpolarized uv-light. Due to $\delta(\text{LCP}) = 230\text{nm}$ the right pixel in Figure 1 acts as a half-wave plate, rotating incident linearly polarized light from polarizer P_1 by 90°. Because the polarization direction P_1 parallels the slow optical axis n_{e2}, the state of polarization of P_1 is not affected by the left pixel of the hybrid LPP-configuration. Therefore, the left pixel is non-transmissive in the crossed polarizer configuration of Figure 1 whereas the right pixel is transmissive.

For our hybrid LPP-concept new cyano biphenyl (CN)-LPP-photopolymers with considerably improved aligning properties and high thermal stability were developed [4]). Like PVMC used previously [1]) the new LPP-materials comprise a cinnamic acid photoreactive group in their side chains. Figure 2 schematically depicts our model describing the anisotropic photoreactions occurring in orthogonally (isotropically) aligned pairs of precursor CB-LPP polymer molecules upon linear photopolymerization [4]).

Prerequisites for transferring photogenerated aligning patterns of CB-LPP-coated substrates into adjacent precursor LCP-films are LCP- and LPP-materials with compatible mesomorphic and surface wetting properties. This was achieved with a room temperature nematic LCP-mixture developed in our labs which comprises diacrylates [6]) of the type,



with different substituents R attached to the central phenyl ring.

The hybrid LPP-configuration with one fully transmissive and one non-transmissive pixel shown in Figure 1 represents a binary phase-retarder pattern. Figure 3 shows a photograph taken of a hybrid LPP phase retarder

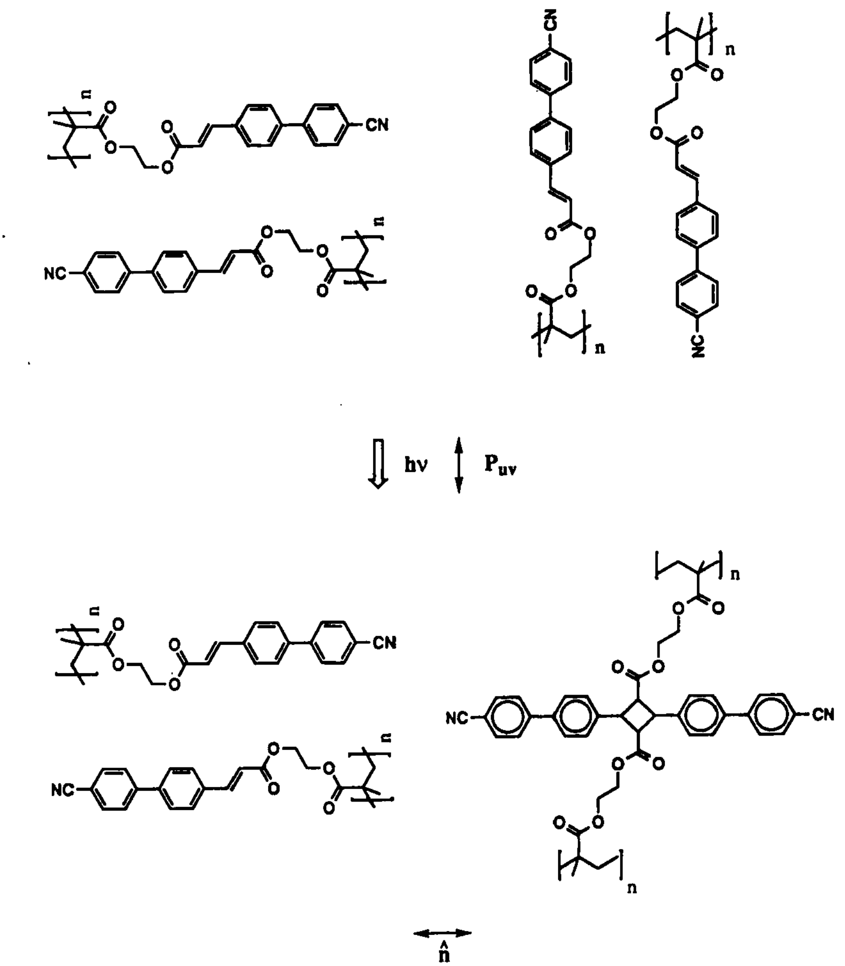


FIGURE 2 Model derived for the anisotropic molecular configurations generated by linear photopolymerization of CB-LPP. P_{uv} = direction of linearly polarized uv-light of $\lambda = 310$ nm, $\hat{n}$ = preferred direction of LPP-induced LC-alignment.

image according to Figure 1 placed between linear polarizers. The high contrast, negative and positive contrast pictures of the retarder illustrate print like optical quality.

Analogous digital configurations can be used for generating more complex retarder images of pictures comprising not only black and white information but also gray tones. Figure 4 schematically depicts the three optical processing steps [5]) which we used for generating a digital hybrid LPP-phase retarder pattern of the gray scale G of Figure 4a. First a digital photo mask was made of

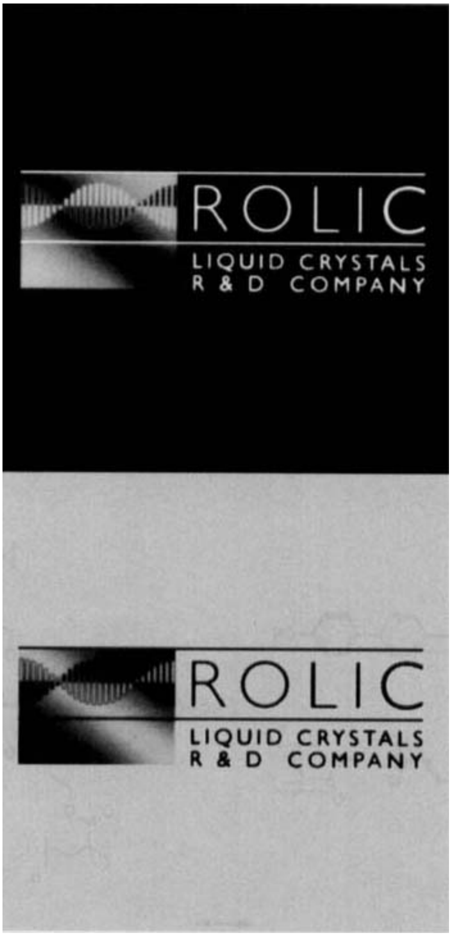


FIGURE 3 Photograph of the hybrid LPP retarder Logo of ROLIC according to (Figure 1 in the negative contrast mode (top: $P_1 \perp P_2$) and in the positive contrast mode (bottom: $P_1 \parallel P_2$).

the gray scale which was then projected onto the LPP-coated glass substrate using vertically polarized uv-light. This leads to the vertically aligned and cross-linked pixellated aligning substrate LPP(1) depicted in Figure 4b. Next, the photo mask was removed and the so far unexposed sample area illuminated (Fig. 4c). Finally, the completely photo-aligned and cross-linked LPP-substrate

FIGURE 4 Illustration of the three processing steps for generating a digital LPP-aligning pattern of the gray scale G on top. M = digital photo mask. For simplicity the photoalignment LPP-directions are drawn parallel to the respective directions of uv-polarization (for CB-LPP they are perpendicular, c.f. Fig. 2). UV-exposure intensity I = 13 mW/cm$_2$ at = λ 310nm; exposure time t(LPP) = 10 sec.

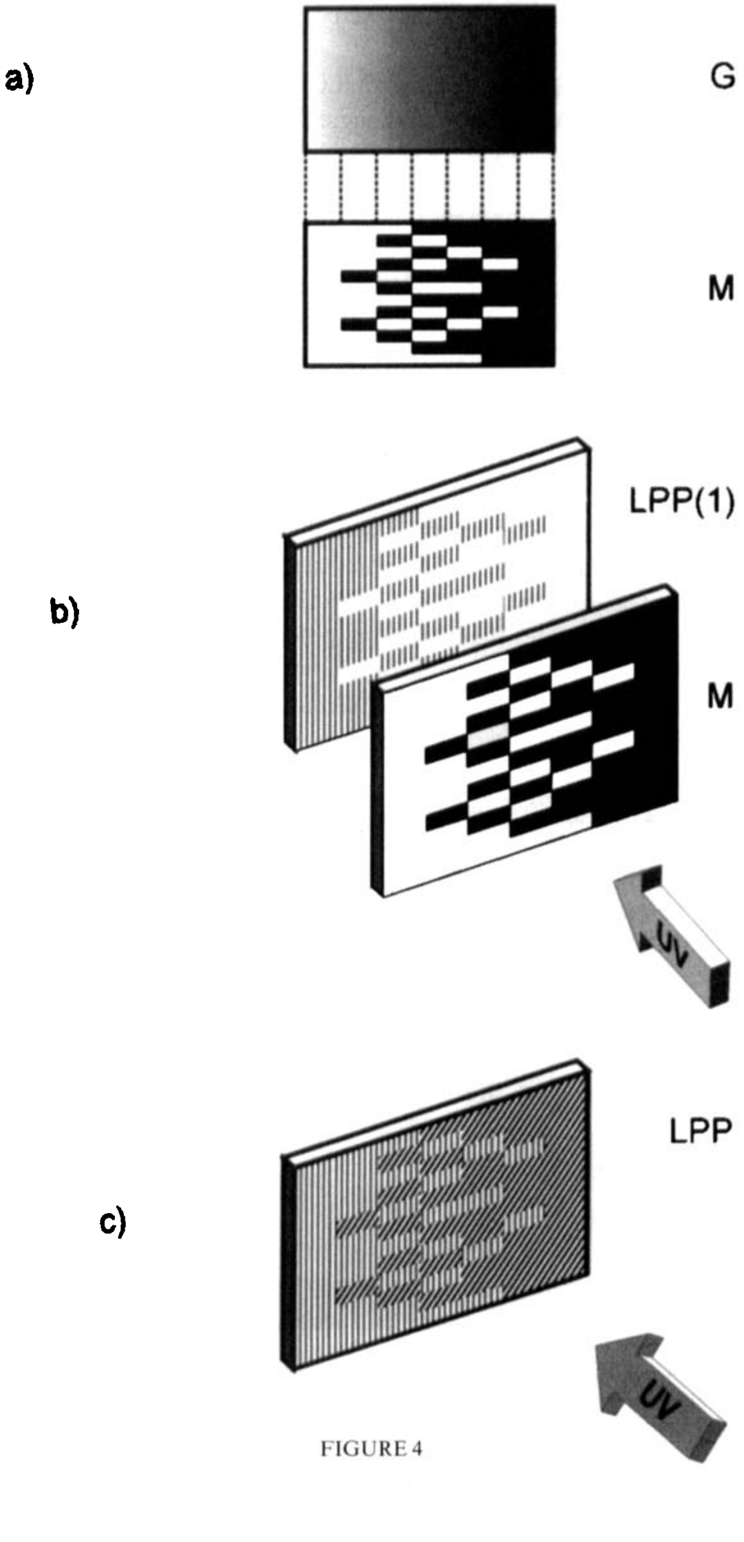


FIGURE 4

was spin-coated with 2 μm thin precursor LCP-layer. After alignment by the LPP-substrate the photo patterned and aligned LCP-layer was conventionally photo-polymerized with unpolarized uv-light, thus transferring the LCP-retarder pattern into the solid state and completing the hybrid LPP-process. These two parallel processing steps render the generation of high information content phase retarder patterns on single substrates feasible.

Figure 5 shows a photograph of Al Saupe's hybrid LPP-phase retarder image on a single glass substrate made in analogy to Figure 4. To visualize the phase information on the framed HLPP-glass substrate, which is invisible in unpolarized light, Alfred's photograph in Figure 5 was taken with the substrate placed partly between crossed polarizers. As a result, the area confined between the polarizers in Figure 5 becomes visible whereas the phase retarder image outside remains invisible (white). The optical configuration of the HLPP-retarder of Figure 5 is identical with the configuration of Figure 1. Its black-white image results from the optical retardation δ(HLPP) = 230 nm $\sim \lambda/2$ chosen. The 6 × 6 cm digital HLPP-image consists of 480 × 480 pixels. The photograph illustrates the interesting potential of the hybrid LPP-technology applied to photo-patternable optical retarders.

Apart from integratable and photopatternable low loss polarization interference filters, polarizers and color compensators for liquid crystal displays,

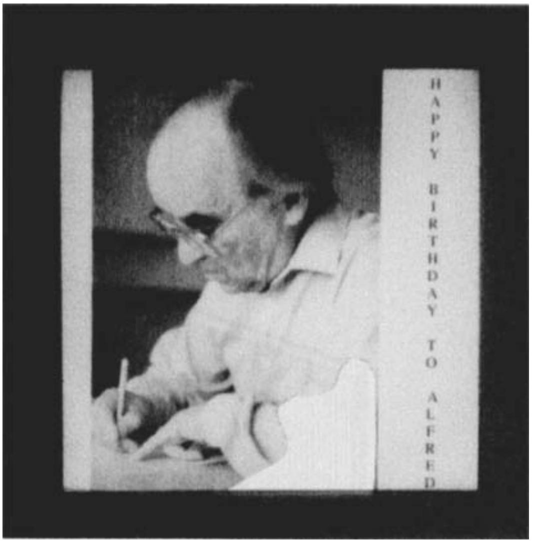


FIGURE 5 Photograph of the complex hybrid LPP-retarder image of Alfred Saupe on a single glass substrate visualized in transmission in white light between crossed polarizers. Only the part of the retarder image confined between crossed polars is visible whereas the image outside remains invisible (white area on lower right side).

hybrid LPP-retarders open-up the possibility for generating copy proof images visible only in polarized light. The LPP-information is detectable with polarisation sensitive detectors in automatic safety control equipment or by visual observation through polarizers. Besides from optically anisotropic multilayers, additional functions can be integrated into hybrid LPP-configurations, such as photopatternable LPP-layers for aligning monomeric liquid crystals in LCDs, or electrode layers for addressing LCDs. [5]) LPP-configurations operate in transmission as well as in reflection; they open-up a plethora of new applications and it is a real pleasure to apply them to my good friend and eminent scientist Alfred Saupe in honor of his seventies birthday.

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