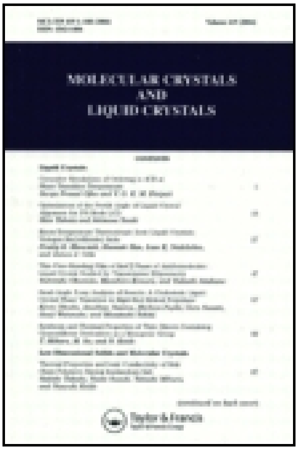

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Polarization Holographic Patterned Alignment of Nematic Liquid Crystals

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We have successfully demonstrated a new way to pattern the alignment of liquid crystals using a linear photopolymerizable polymer (LPP) alignment layer with a polarization interference holographic exposure. This exposure method establishes a continuously periodic alignment of liquid crystals on the micrometer scale. In this contribution we show the various liquid crystal configurations that can be achieved through technique that have potential switchable diffractive optics applications.

Keywords: alignment layer; holographic gratings; photopolymerizable polymers

INTRODUCTION

Surface Patterning

Patterned alignment layers for liquid crystal materials have received much attention over the past decade for applications in display, telecommunication and optical security technologies. Creating patterned alignments of liquid crystal in multi-domain configurations is a very attractive technique for improving the viewing angle of a single domain liquid crystal displays. Additionally, periodically varying

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alignments of liquid crystal can be useful for switchable diffractive elements in telecommunication switches or multi level security features.

There have been a number of research groups working with various methods to create multi-domain liquid crystal alignment using conventional polyimides. Bos and coworkers have demonstrated a four-domain liquid crystal configuration using lithographic masking and a reversed rubbing process [1,2]. Wen and coworkers have shown through atomic force microscopy scribing the ability to create herringbone structures of liquid crystal alignment for switchable gratings [3]. Versteeg and coworkers have shown patterned alignments of liquid crystal using a direct laser writing process for security applications [4]. Varghese and coworkers have demonstrated a four-domain liquid crystal configuration using a micro-rubbing process for wide viewing angle displays [5]. Gibbons and coworkers have shown that polyimides doped with azo dyes can be patterned with a laser to create grating-like structures [9].

In addition to patterning polyimide materials, photopolymerizable materials have been demonstrated to create patterns of liquid crystal alignment. Rather than using a convention rubbed polyimide where a velvet of felt cloth comes in direct contact with the alignment layer, a photopolymerizable material is coated on a substrate and illuminated with ultraviolet (UV) light. In linear photopolymerizable polymer (LPP) alignment layers, the UV irradiation causes a selective polymerization in the direction of the incident polarization which aligns the liquid crystal in the same direction [6]. There have been a number of materials that exhibit alignment properties that accomplish the same goal, including: cinnamates [7], polyimide [8], dye doped polymers [9], and self assembled monolayers [10]. Multiple alignment configurations have been achieved by photolithography masks and multiple UV exposures [7,10]. In this contribution we focus on a new method for creating patterned alignment of liquid crystal using a linear photopolymerizable polymer with polarization interference holography.

Polarization Holography

The premise of using holographic exposure techniques allows for a plethora of new configurations that can not be achieved through lithographic masks and multiple exposures. From this technique both amplitude and polarization interference patterns can be recorded on photoalignment layers to make a variety of periodic alignment configurations.

Amplitude interference is achieved by interfering two coherent beams having the same linear polarization. The interference pattern created from this holographic exposure results in a modulation of the light beam intensity with a constant polarization. The fringe spacing of the intensity modulation is governed by Bragg's law. A schematic illustration of this amplitude interference is shown in Figure 1(a).

One exposure method that results in a polarization grating is formed by interfering incident laser beams with orthogonal linear polarizations. In this case, the resulting polarization spatially transforms from linear to elliptical to circular polarization and the amplitude remains constant as shown in Figure 1(b). The spatial periodicity of the polarization is determined by Bragg's law.

The second type of polarization grating is formed by interfering right handed and left handed circular polarized beams. In this holographic exposure the resulting polarization pattern is linear polarization that spatially rotates 2π and the amplitude remains constant.

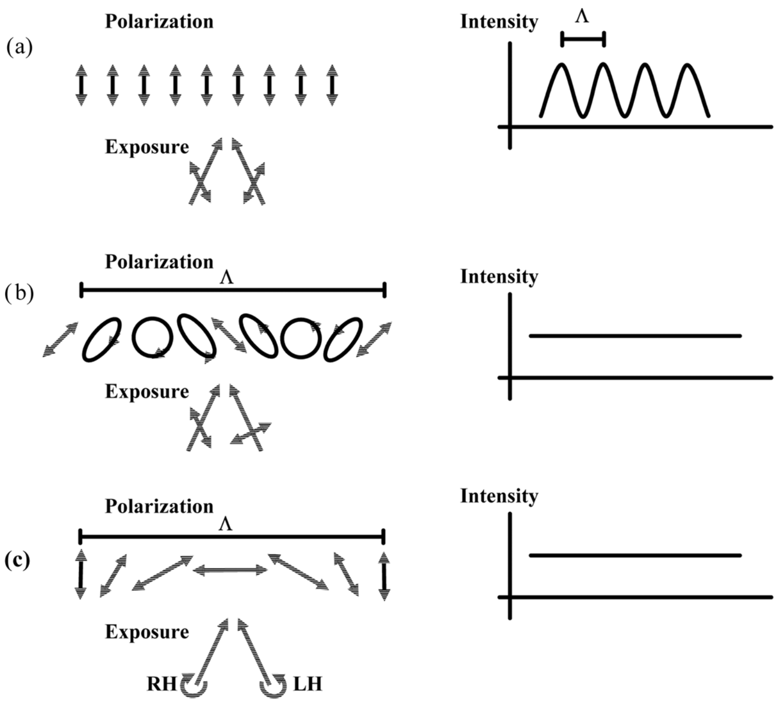

FIGURE 1 Schematic illustration showing three possible holographic exposure methods depicting the polarization and intensity profiles: (a) amplitude interference from two linear polarized beams, (b) polarization interference from two linear orthogonal polarized beams and (c) polarization interference from right handed and left handed circular polarized beams.

A schematic illustration of this type of polarization grating is shown in Figure 1(c). Polarization gratings have also been studied with azo-polymers [11], polymer dispersed liquid crystal (PDLC) systems [12], photorefractive crystals [13], and guest host systems [14].

EXPERIMENTAL

Photosensitive substrates were prepared using linear photopolymerizable polymer (LPP F301) commercially available from Vantico Industries (www.huntsman.com). The LPP material was spin coated on indium tin oxide (ITO) conducting glass substrates with a uniform film thickness of $\sim$100 nm. Residual solvent in the LPP photoalignment layer was removed by heating the substrates on a hotplate at 80°C for 15 minutes. Samples were fabricated by sandwiching two substrates together forming an empty cell with photoalignment layers facing each other; a constant cell gap of 5 μm was maintained using glass fiber spacers. Single holographic exposures were carried out using an Ar^+ laser (Coherent Innova 70) operating in $\lambda = 351$ nm having beam intensities of $\sim$20 mW/cm^2. After the holographic exposure, nematic liquid crystal was filled into the empty cell in the isotropic phase on a hot plate and cooled to room temperature in ambient conditions. Optical characterizations of the liquid crystal alignment were verified using optical polarizing microscopy.

AMPLITUDE INTERFERENCE

Amplitude interference patterns were recorded on the linear photopolymerizable polymer (LPP) coated substrates with two linear s-polarized beams. In the bright fringes of the intensity pattern the LPP material preferentially polymerized in the direction of the incident polarization, while the LPP the dark fringes of the interference pattern were left unpolymerized. When liquid crystal material came in contact with the photoalignment layer after the holographic exposure, the polymerized regions aligned the liquid crystal in the direction of the polarization. The regions that were not polymerized by the holographic exposure did not produce a preferential alignment for the liquid crystal. From this type of holographic exposure process we can create well-organized and disorganized regions of planar alignment that is periodic. The periodicity of the alignment corresponds to the fringe spacing determined by the holographic exposure. An optical polarizing microscopy image of this configuration between crossed polarizers is shown in Figure 2(a). The dark grating lines correspond to regions of well-defined planar alignment and the bright grating

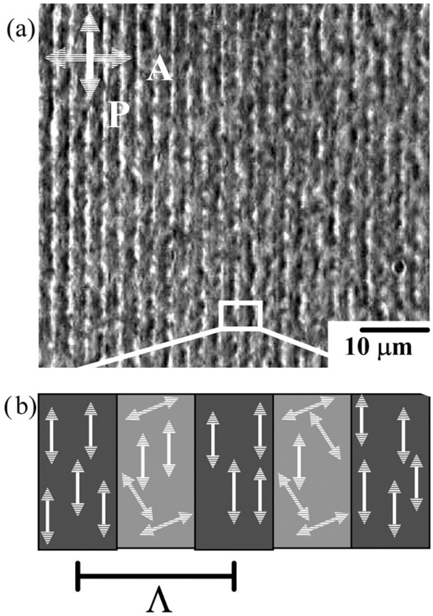

FIGURE 2 Amplitude interference pattern showing: (a) optical polarizing microscopy image and (b) illustration of periodic alignment of liquid crystal in planar aligned and unaligned regions.

lines correspond to regions with planar alignment of a more disorganized nature. A schematic illustration of this alignment texture is shown in Figure 2(b) with arrows indicating the liquid crystal alignment direction.

POLARIZATION CONFIGURATIONS

1-D Polarization Gratings

Polarization gratings were created from the interference pattern of a right and left handed circular polarized beams as shown in Figure 3. By combining this resulting interference pattern with a linear photo-polymerizable polymer alignment layer the exposed regions create a linear polymerization that follows the direction of the continuously rotating linear polarization. When liquid crystal is added to this alignment layer after the exposure process, the molecules respond to the spatially varying linear polarization and mimic the alignment direction established by the polymerization. The result is a continuously changing the orientation of the liquid crystal a periodic fashion over

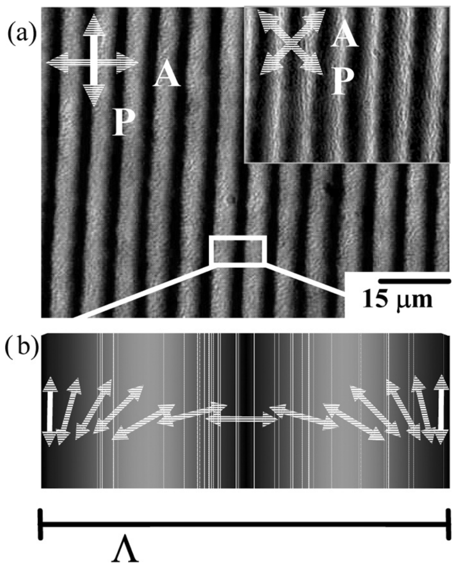

FIGURE 3 Polarization interference grating created from right handed and left handed circular polarized beams showing: (a) optical polarizing microscopy image of grating between crossed polarizers and at 45 between crossed polarizers (inset) and (b) the continuously rotating periodic planar alignment of liquid crystal created from this interference pattern.

macroscopic distances. The periodicity in length corresponds to the grating pitch dictated by the angle of interference between the two circularly polarized beams.

Optical polarizing microscopy images of this polarization grating using a photosensitive alignment layer and nematic liquid crystal are shown in Figure 2. The image shows a polarization grating between crossed polarizers where the grating vector is at 45° with respect to both the polarizer and analyzer. The dark regions of his microscope image correspond to liquid crystal molecules oriented parallel and perpendicular to either the polarizer or analyzer, and the grey regions correspond to liquid crystal molecules transitioning between these two polarizations. The inset of this Figure 3(a) shows an overlapping image of the same grating location cut away to show the contrast inversion when the grating vector is crossed with respect to the polarizer and analyzer. The schematic illustration of the spatially varying liquid crystal alignment produced from this holographic exposure is shown in Figure 3(b). The arrows are used to indicate the average liquid crystal alignment.

2-D Polarization Gratings

A second class of polarization gratings created from the interference pattern of right and left handed circular polarizations, can be formed by rotating one of the photoalignment coated substrates by 90° after the exposure process is complete. When filled with liquid crystal, this cell configuration mimics the alignment caused by the polymerization thus creating multiple domains of liquid crystal alignment from the overlapping regions of the continuously rotating planar alignment that exist on each of the two substrates. The intersecting square 'pixels' that are created from this single exposure, each incorporate a varying degree of twist through the thickness of the cell, that spatially vary in the azimuthal plane of the sample. An optical polarizing microscopy image a multi-domain pixilated sample is shown between

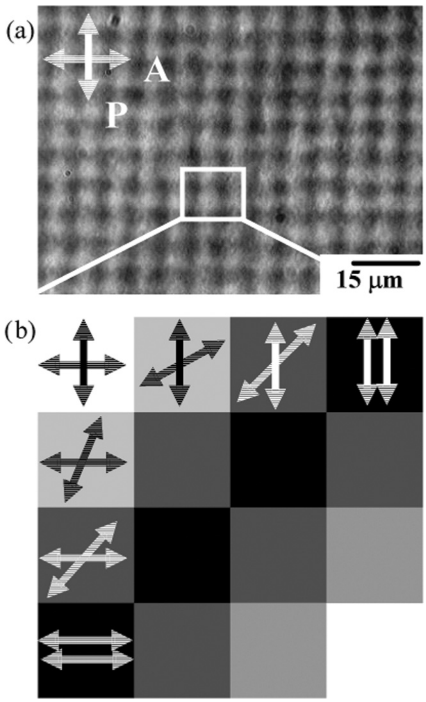

FIGURE 4 A two dimensional grating created using polarization interference from a right handed and left handed circular polarized beams where the alignment directions are orthogonal to each other. The optical polarizing microscopy image of this grating is shown in (a) with an illustration of the liquid crystal alignment shown in (b).

crossed polarizers in Figure 4(a). The schematic illustration shown in Figure 4(b) represents the pixilated domains created from the polarization exposed substrates that have been created in an orthogonal direction. The white pixels correspond to a 90° twist configuration of the liquid crystal, and the black pixels represent a planar alignment (0° twist) of the liquid crystal when placed between crossed polarizers. The different grey level pixels represent the different twist degrees of the liquid crystal configuration ($0° < \text{twist angle} < 90°$). Future research will focus on this configuration with extensive measuring electro-optic response and using nuclear magnetic resonance to determine ordering and additional alignment information.

Hybrid Configurations

It is also possible to achieve hybrid configurations of periodic liquid crystal alignments using various surface treatments. By using the polarization pattern from the linear photopolymerizable polymer (LPP) alignment layer on one substrate the second substrate can have either a planar or homeotropic alignment as shown schematically in Figure 5(a) and (b).

These configurations are just a few of the many possible alignment configurations that can be possible with a periodic alignment established through holographic exposure techniques. We believe that these

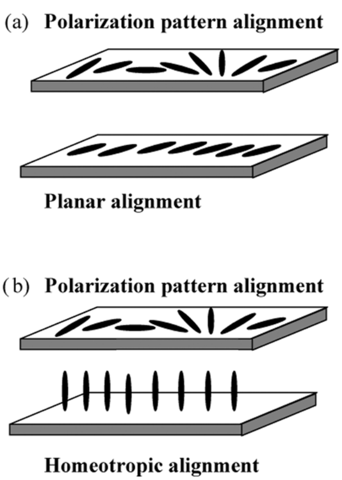

FIGURE 5 Examples of hybrid configurations using the polarization interference alignment on one substrate and (a) planar (b) homeotropic alignment on the second substrate.

novel configurations can be useful in device applications and will provide excellent physical systems for researchers to study on the macroscopic scale and molecular scale using both experimental and theoretical approaches.

CONCLUSION

We have shown a novel technique to pattern continuously varying liquid crystal alignments using polarization holography. The versatility of the holographic exposure technique allows for a plethora of liquid crystal configurations that are otherwise not possible with conventional alignment or lithographic methods. We have demonstrated only a few of the many possible configurations using this technique for this initial contribution, but plan to focus attention on the other the other alignment configurations with electro-optic measurements and modeling in future publications.

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