

Gradient pretilt angle alignment materials with different photosensitivity for tunable polarization-independent self-aligned liquid crystal lens

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Abstract

Alignment of benzaldehyde materials with different photosensitivity thresholds, capable of changing the pretilt angles of nematic liquid crystal (LC) from 90° to 0° in a controlled manner under UV-B exposure, has been developed. Inhomogeneous exposure of uniform rubbed alignment layers allows the formation of a refractive index gradient inside the LC cell. The concept of tunable polarization-independent self-aligned LC lens based on gradient pretilt angle alignment materials with different photosensitivity is demonstrated. Self-alignment of two polarization-dependent sub-lens is achieved due to a single exposure act of two alignment layers, which are located on the same piece of glass on both sides, forming one common optical axis for a polarization-independent LC lens. The sub-lens cells have uniform cell gap and are independently controlled using low-voltage driving. Devices based on gradient benzaldehyde alignment materials can be used in many modern optical and photonic devices.

KEYWORDS

gradient alignment materials, polarization-independent LC lens

1 | INTRODUCTION

The alignment material for liquid crystal (LC) with the ability to set the pretilt angle gradient allows the implementation of various passive or active LC devices and optical elements such as diffraction gratings, lenses, waveguides, and others.¹ Various complexity structural implementations of the tunable LC lenses have been reported,^{2–5} while one of the most technological fabrication methods is based on the application of gradient alignment materials.^{6–8} This method will improve a number of disadvantages inherent in LC lenses^{9,10}: a large number of defects, limiting the maximum and minimum diameter; the necessity of thick devices for high optical

power; the derived response time of thick devices; the high voltage required to change the refractive index; the polarization dependency of LC lenses; and others.

Alignment materials with a variable pretilt angle are subject to high requirements: the high anchoring energy, pretilt angles reproducibility, defect-free orientation, low control voltages to change the refractive index, etc. All these requirements are fulfilled via the application of gradient alignment layers for the creation of tunable LC lenses,^{6,11,12} based on photosensitive alignment materials with the following properties:

- Low alignment material baking temperature 70–90°C
- Standard rubbing alignment process

- Increased anchoring energy of the alignment layer
- UV-B sensitivity in the range of 300–330 nm
- Reproducible monotonic change of the pretilt angle from 90° to 0° under non-polarized UV-B exposure
- Adjustable photosensitivity threshold of the alignment layer predetermined by monomers ratio in the course of copolymerization
- No absorption in the visible spectral range
- High photostability of photoalignment properties.

UV and thermal stability of benzaldehyde alignment materials have been checked by Mahilny et al.¹³ and showed good results.

Common LC lenses are polarization-dependent, focusing the incident rays with an electric field corresponding to the alignment direction of the LC lens, and rays with orthogonal polarization pass through it without changes.¹⁴ Using a polarizer in front of the LC lens allows us to select the appropriate rays with the necessary polarization and improve the characteristics of the LC device. However, this approach sacrifices brightness and reduces the efficiency of LC lenses application in optical devices; therefore, the most promising direction for the development of LC lenses is the creation of polarization-independent devices. Various methods for manufacturing polarization-independent LC lenses are proposed.^{15–17} A polarization-independent LC lens can also be formed when the LC is oriented on the surface of

the substrates in the orthogonal direction; in this case, the near-surface layer of the LC acts as a working element.¹⁷ The combination of two round polarization-dependent LC lenses with a mutually perpendicular orientation direction is the technique, which raises the problem of the mutual positioning of the two lenses.^{14,18} The resulting image from such lenses will consist of two images formed by each lens independently, and when the two lenses are made independently, an offset always takes place. The mutual exact combination of two lenses, or else self-alignment, is the solution to this problem. Development and application of gradient alignment materials with different photosensitivity for getting polarization-independent LC lens, consisting of two independently tunable polarization-dependent sub-lenses, located in one tunable LC cell, and consisting of three glass substrates (Figure 1), is the aim of this work.¹⁹

2 | EXPERIMENT

2.1 | Gradient alignment materials with different photosensitivity thresholds

We investigated LC director inclination on the gradient pretilt angle alignment materials (GPAAM) comprising 40%_{mol} (GPAAM1) and 25%_{mol} (GPAAM2) of vertical alignment groups in the course of UV irradiation of alignment layers. Glass substrates were coated with thin polymer layers (45–80 nm) from a 2% solution of GPAAM in butyl acetate by the rod-coating method²⁰ (or draw-bar coating method²¹). After drying at 70° for 5 min, the layers were uniformly rubbed with a cloth and exposed to unpolarized UV-B light of T8-UVC-15 W-G13 (AerVita, Russia) fluorescent tube lamp under the intensity of 4 mW/cm². The surface of GPAAM layer was divided into several areas that were irradiated for various time intervals. The substrates were assembled in antiparallel LC cells with 20 µm cell gap. The cells were filled with LC E7 ($n_o = 1.61$, $n_e = 1.83$, $\Delta n = 0.22$, $\lambda = 550$ nm, $t = 20^\circ$) and hermetically sealed. The pretilt angles were measured by the cell rotating method between crossed polarizers²² at the He-Ne laser wavelength of 0.633 µm.

2.2 | Self-aligned polarization-independent LC lens design and fabrication

Self-aligned polarization-independent LC lens based on GPAAM with different photosensitivity consists of three substrates arranged in the form of a sandwich. A layer of 40–80 nm of vertical alignment material was spin-coated

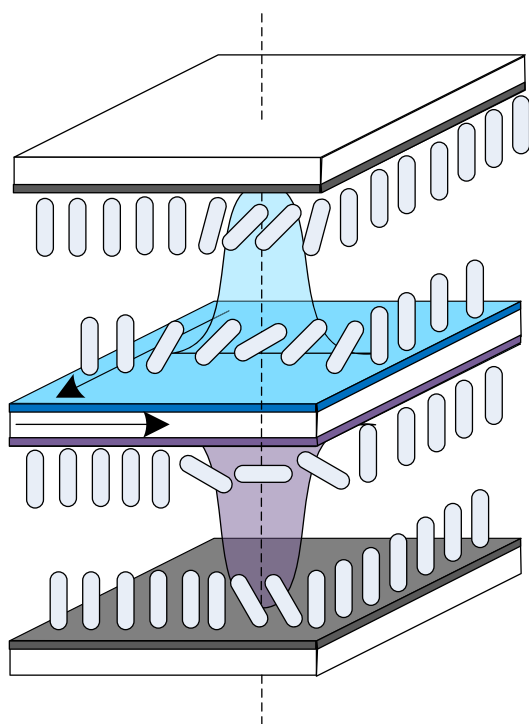


FIGURE 1 Polarization-independent LC lenses structure

from 1%_{mass} solution in butyl acetate at 3000 Rotation Per Minute (RPM) for 60 s on two outer 1-mm-thick ITO glass substrates, baked at 90°C on a hot plate for 5 min, and then irradiated with uniform unpolarized UV-B exposure for 5 min.

GPAAM 1 and GPAAM 2 were deposited on both sides of the Indium Tin Oxide (ITO) glass substrate, located in the middle of the sandwich structure of the LC cell. Double-sided ITO-coated glass substrate was used as the middle substrate of the LC cell (Figure 2).

A 1%_{mass} solution of GPAAM1 polymer in butyl acetate was spin-coated on one side of a glass substrate at 3000 RPM for 60 s. The substrate was baked at 90°C on a hot plate for 5 min. Then, a 1%_{mass} solution of GPAAM2 polymer in butyl acetate was spin-coated on another side

of a glass substrate at 3000 RPM for 60 s. The substrate was again baked at 90°C on a hot plate for 5 min. The alignment layers were rubbed in orthogonal directions with a cloth as in the standard alignment layer rubbing process and exposed via a “round hole” photomask with UV lamp radiation. During the irradiation, a centrosymmetric exposure field with a bell-shaped distribution of illumination was formed.²³ Such exposure conditions provide a light intensity distribution required for the induction of the LC lens pretilt angle gradient. The spacing between the photomask and the alignment layer was 0.5 mm. The diameter of the round hole and the exposure time were 1,5 mm and 32 min, correspondingly. The cell gap of 20 μm was fixed by fiber spacers. Finally, the cell was filled with LC E7 and hermetically sealed.

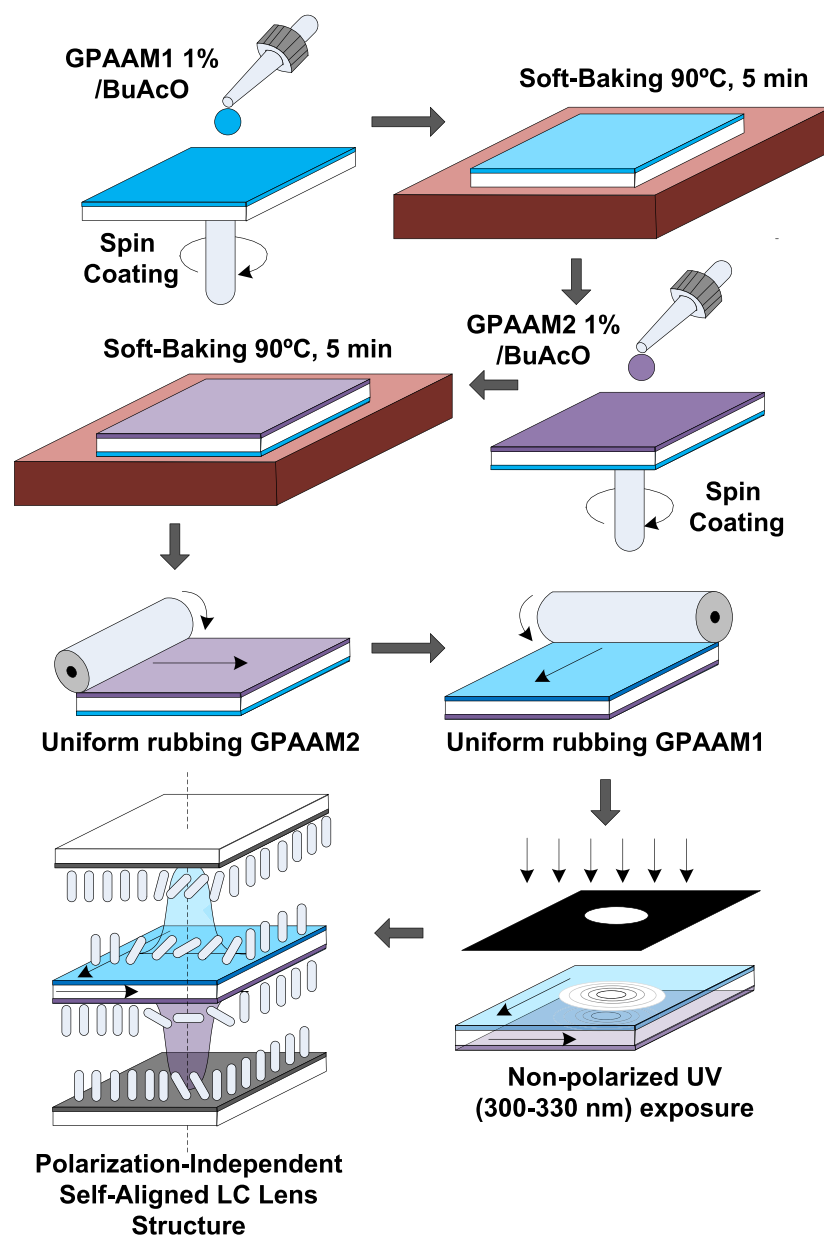


FIGURE 2 Process flow of self-aligned polarization-independent LC lenses fabrication

3 | RESULTS AND DISCUSSION

The pretilt angles of the GPAAM1 and GPAAM2 layers on the UV exposure time under uniform irradiation were measured and applied for LC lens fabrication.⁶ The gradual decrease of sensitivity thresholds from vertical to the planar state is demonstrated in Figure 3 for GPAAM2 and GPAAM1. In the first case, the decrease develops in the approximate range 0.24–1.92 J/cm²; in the second case the range is shifted to 1.92–7.68 J/cm².

The experimental uncertainties in the values of the pretilt angles from the exposure dose are estimated to vary from 0.5° to 2°.

In order to be able to apply a voltage potential to both cells of the polarization-independent LC lens, we used double-sided ITO-coated glass substrate of 0.1 mm thickness. Such a glass substrate has transmittance in the

UV-B region (300–330 nm) about 10% (Figure 4). That means that alignment material on the bottom side of the substrate receives 10 times smaller light dose than the material on the top side.

However, the shape of the light intensity distribution that induces lens pretilt angle gradient of the alignment layer remains the same, as well as the mutual alignment of the centers of the light spots at the top and bottom sides of the double-sided ITO glass substrate. It gives the requirement for the sensitivity of the alignment materials deposited on the top and bottom sides of the intermediate substrate: on the bottom side material of 10-fold higher sensitivity is required (Figure 5). Accordingly, in Figure 3 there is rough compliance of GPAAM1 and GPAAM2 photosensitivity with this condition.

Exposure of two layers of alignment materials in one step provides self-alignment of the optical axes of two

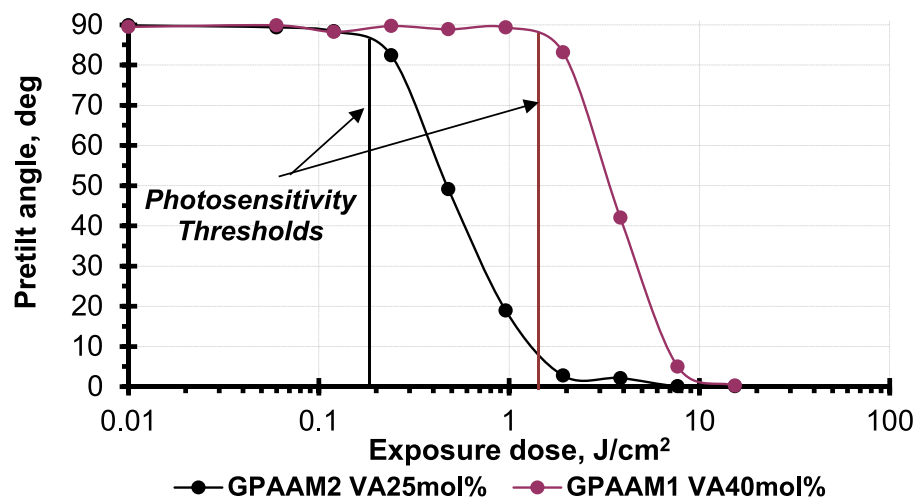


FIGURE 3 The pretilt angle dependences on UV light exposure dose for GPAAM1 and GPAAM2

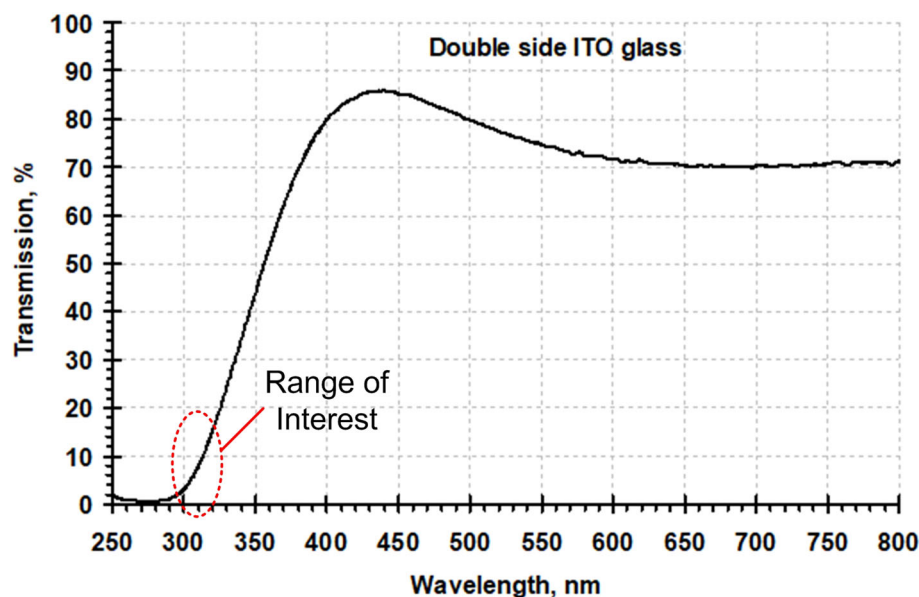
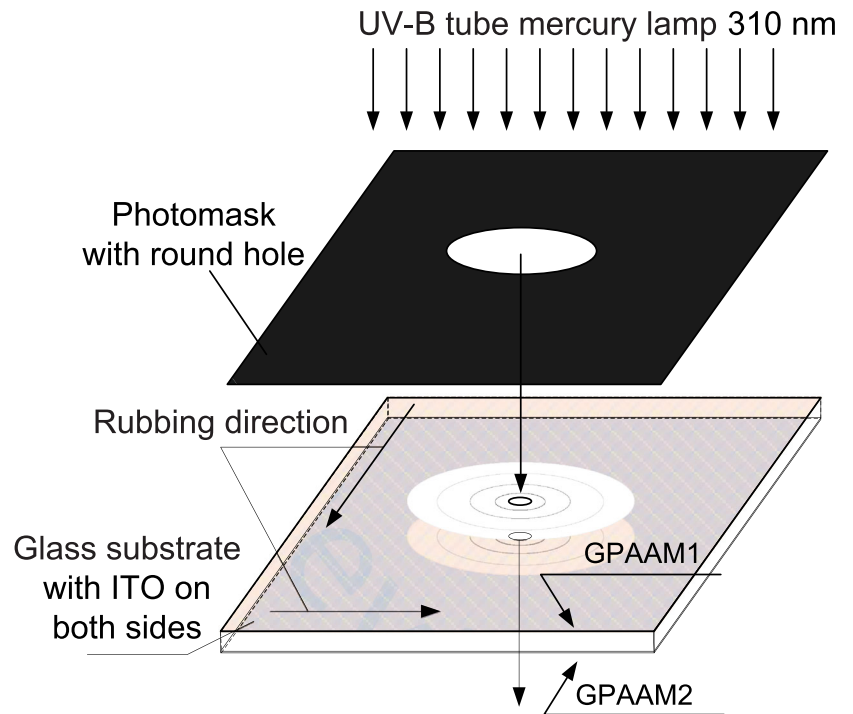


FIGURE 4 The transmission spectrum of double-sided ITO glass substrate of 0.1 mm thickness

FIGURE 5 Self-aligning exposure scheme of the alignment layers on the intermediate substrate

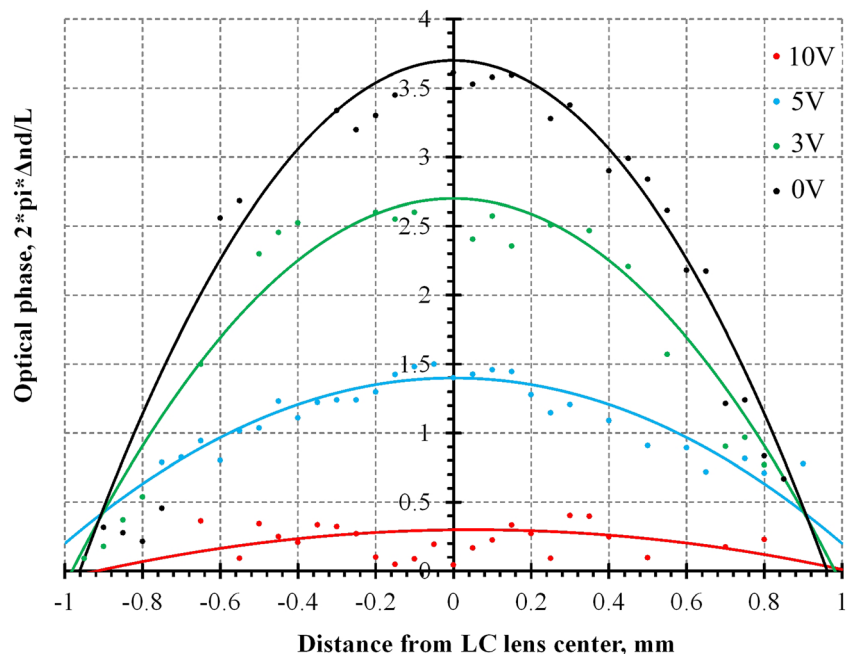


lenses formed due to the gradient of the pretilt angle on the upper and lower sides of the substrate and, therefore, the common optical axis of both cells for a polarization-independent LC lens.

The fabricated LC lens comprises two sub-lenses, which have two electrodes each at top and bottom substrates, and can be controlled independently. The axes of the sub-lenses are orthogonal to each other. The exact identity of pretilt angle distribution and the same

thickness of the sub-lenses should result in mutual birefringence compensation. In that case, the phase gradient of the polarization-independent LC lens is not observed in the polarization microscope when the lens axes are at 45° to the crossed axes of the polarizer and analyzer. Actually, in our experiment optical transmission of the system measured with spectrometer Ocean Optics HR4000CG UV-NIR (USA) within the lens was constant in the limits of 5%. This confirms the high degree of

FIGURE 6 Direct measurements of LC sub-lens optical phase distribution for applied voltage levels of 0, 3, 5, and 10 V



similarity of phase distributions for both sub-lenses under zero voltage.

To observe and analyze optical phase distribution, independent control of the LC lens sample was used. First, a high voltage level of 15 V was applied to the top sub-lens to turn the lens off by switching the LC into a uniform vertical orientation. Then different voltage levels of 0 to 10 V were applied to the bottom one. As shown in Figure 6 10 V is sufficient to transfer the LC of the sub-lens into a vertical state and almost completely transform it into a uniform phase plate, which corresponds to the lens with infinite focal length. We conclude that the operating voltage levels of the obtained LC lens for tunable focal length are below 10 V.

Optical phase measurement accuracy was better than 0.1

The diameter of the developed LC lens is voltage dependent and unlike a common lens is not a constant. Thus, LC lens diameter is about ~ 2.0 mm for 10 V, and it increases to 2.5 mm for 3 V of applied voltage level. It is the specific property of the pretilt angle gradient LC lens fabricated by the developed exposure technique with a round hole photomask. Probably, it is related to the elastic properties of LC and its interaction with gradient alignment material.

The UV lamp spectrum affects the reproducibility of the phase profile values in Figure 6. It has been noticed that significant light interference occurs at the glass thickness on using low-pressure mercury lamp or laser “coherent” radiation, which affects the actual localized pretilt angle value. Thus, non-uniform pretilt angle gradient takes place inside the cell, which in our case led to the values spread of the LC lens phase profile (Figure 6). Utilization of wide bandwidth non-coherent LED light sources is one of the possible solutions.

Key features of the polarization-independent LC lens:

- One LC cell with three substrates is applied;
- the photosensitive layers at the intermediate substrate are exposed simultaneously in one step to provide self-alignment of LC gradient structures;
- independent control of the sub-lenses can be used to adjust their focusing LC distributions;
- low level of control voltages.

4 | CONCLUSIONS

GPAAMs with different photosensitivity threshold and their application for self-aligned polarization-independent LC lens are presented. The polarization-independent LC lens based on GPAAMs consists of two

polarization-dependent LC sub-lenses both with a uniform cell gap. Self-alignment is realized through simultaneous exposure of alignment layers with different photosensitivity coated on both sides of the double-sided ITO glass substrate. Polarization independence is achieved by the perpendicular crossing of the azimuthal alignment direction of the polarization-dependent LC lenses. These LC sub-lenses are controlled in parallel with low *alternating* current voltage levels 0–12 V. The materials were successfully applied for polarization-independent self-aligned LC lens fabrication.¹⁹

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