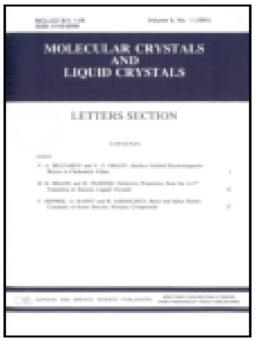

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Tunable Liquid Crystal Lens Based on Pretilt Angle Gradient Alignment

V. S. Bezruchenko[a,b], A. A. Muravsky[a], A. A. Murauski[a], A. I. Stankevich[b], and U. V. Mahilny[b]

[a]Institute of Chemistry of New Materials, NAS Belarus, Minsk, Belarus; [b]Physical Department of Belarusian State University, Minsk, Belarus

ABSTRACT
The new method of LC lenses fabrication based on innovative alignment material for pretilt angle gradient generation is developed. The alignment layer provides LC lens pretilt angle gradient via two-step treatment: uniform rubbing and gradient nonpolarized UV exposure. LC lens has uniform cell-gap, 2–10 V tunable voltage range. The fabrication method is scalable for lens arrays for two-dimensional/three-dimensional autostereoscopic and light-field displays.

KEYWORDS
alignment material; liquid crystal lens; photosensitive polymer; pretilt angle

1. Introduction

Since first announcement of liquid crystal (LC) lens about 40 years ago [1], a large number of different designs of LC lenses capable to focus light are developed. The recent increase of interest to switchable LC lenses and lens arrays is coming from the possibility of its application for Lytro cameras, two-dimensional/three-dimensional (2D/3D) autostereoscopic and light-field displays for 3 D capturing and imaging.

A large number of different LC lens fabrication methods are known [2, 3]. Typical drawbacks are: nonuniform thickness of LC layer, low switching speed of LC lenses (several seconds), high levels of control voltage (50 V and above), etc. So far, standard method of LC lens fabrication has not been established yet. We propose new LC lens fabrication method based on application of our innovative gradient alignment material, special photosensitive polymer that possesses photocontrollable pretilt angle and allows formation of target pretilt angle gradients upon processing. Specifying pretilt angle gradient from vertical to planar by alignment layer, sets spatial distribution of tilt angle in the bulk of LC layer that defines the spatial distribution of refractive index when light passes through the LC cell. The distribution of the refractive index is capable to change in a low voltage control manner creating electrically tunable focal length.

There are several advantages in our approach over other methods:

- Fabrication complexity of LC lenses array is comparable to manufacture of passive-matrix LC cell.
- Ability to switch optical lenses on and off with voltage.
- Tunability of LC lenses organized in LC lens array with only two control electrodes comprising simultaneous tuning of the focal length of all lenses.
- Low voltage control.

CONTACT V. S. Bezruchenko Veronika.Bezruchenko@gmail.com Institute of Chemistry of New Materials, NAS Belarus, St. F.Skoriny 36, 220141, Minsk, Belarus.
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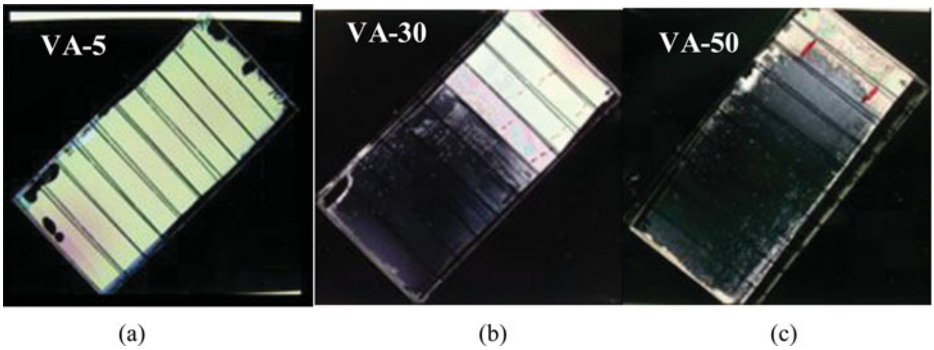

Figure 1. LC cells with the alignment layers containing different percentages of VA: (a) 5, (b) 30, and (c) 50 mol.%, between crossed linear polarizers. The exposure dose varies from 0 to 15.4 J/cm^2 within each cells' area.

The target application of the developed LC lens fabrication method is creation of LC lens arrays for light-field Lytro cameras, 2D/3 D switchable autostereoscopic, and light-field 3 D displays.

2. Composition and properties of the gradient alignment material

The new gradient alignment material expands the line of photosensitive polymers with benzaldehyde side groups demonstrating bulk and surface photoinduced anisotropy [4–6]. It has been created on the basis of the benzaldehyde methacrylic alignment polymer of M series [7]. The new polymer is characterized by the percentage of three components and its macromolecules comprise photosensitive benzaldehyde-containing fragments (B), methacrylate fragments, causing vertical LC alignment (VA), and methacrylate fragments producing planar LC alignment under photocrosslinking of the material. The distinctive feature of the material is the two-step process of alignment layer surface treatment changing tilt angle: standard rubbing step that defines the azimuthal direction of LC alignment, and the nonpolarized inhomogeneous UV exposure step that forms pretilt angle profile on the alignment layer. Immediately after rubbing the alignment layer, creates LC orientation with maximal pretilt angle (homeotropic under considerable VA contents). As a result of photocrosslinking under UV irradiation, anchoring properties change. These changes lead to a decrease of pretilt angle and finally the LC orientation become planar.

The exposure range, within which pretilt angle decreases, strongly depends on the correlation of B and VA mol.%. Nine alignment materials with percentages of VA 5, 7.5, 10, 15, 20, 25, 30, 40, and 50 mol.% have been investigated, while content of B was constant and equaled to 10 mol.%. The alignment layers were prepared on glass substrates from 2% BuOAc solution using Mayer-rod coater [8]. After soft-baking (5 min at 70°C), the uniform rubbing was carried out that defined the azimuthal direction of orientation. Under final treatment step of the alignment layer, nonpolarized UV exposure, various values of pretilt angle were specified. The alignment layer surface was divided into 10 areas which were exposed with UV-B tube mercury lamp radiation to different doses. Irradiance of the layer surface was 4 mW/cm^2 in the spectral range 300–320 nm. Antiparallel LC cells with 20 μm cell-gap were assembled and filled with E7 liquid crystal. On the photographs of the LC cells placed between crossed linear polarizers (Fig. 1), transversal stripes correspond to the areas homogeneously exposed for certain time from 0 to 64 min. The brighter the stripe the less the pretilt angle of LC director. Dark areas represent homeotropic alignment.

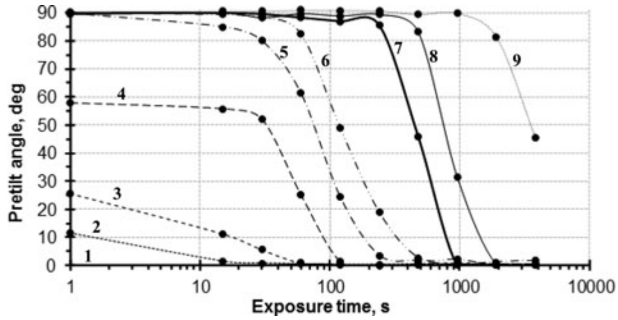

Figure 2. Pretilt angle dependencies on exposure time for the alignment materials with various percentages of VA: 1–5, 2–7.5, 3–10, 4–15, 5–20, 6–25, 7–30, 8–40, and 9–50 mol.%.

The pretilt angles were calculated from the dependences of optical transmittance of the LC cell in between crossed linear polarizes on the angle of light beam incidence onto a plane of the cell [9–11]. LC cell was rotated along the axis within the plane of the cell perpendicular to the rubbing direction. The beam of He-Ne laser crossed the LC cell at the axis of rotation. The accuracy of the motorized angular positioning was 0.05° in the range of ± 70°, sampled with 1° step.

The alignment materials with various percentages of VA were investigated measuring the pretilt angle dependencies on the exposure time (Fig. 2). Initial homeotropic orientation occurs once the VA content become higher than 20 mol.% (Fig. 2, curve 5). On irradiation the pretilt angle magnitudes gradually diminish to zero for all observed materials having VA contents below 50 mol.%. We conclude that the most appropriate alignment material for LC lens creation is the polymer with VA content 30 mol.%, providing least defects at vertical and planar alignment conditions (Fig. 2, curve 7).

3. Fabrication of LC lens

The LC lens is obtained with the uniform cell-gap due to axially symmetric gradient of the director orientation (Fig. 3(a)). The gradient of the LC director distribution leads to respective variation of the LC birefringence and the refraction index for appropriate polarization.

The cell of the liquid crystal lens comprises two glass substrates with ITO electrodes. The top and the bottom substrates have different alignment layers. Homogeneous vertical alignment layer is coated on the top substrate, while alignment layer with gradient pretilt is deposited on the bottom substrate. As seen in Fig. 3(a), at no voltage state the inhomogeneous distribution of LC director creates the lens-shaped structure with minimal focal length while at on-state uniform director distribution can be achieved giving the infinite focal length (Fig. 3(b)).

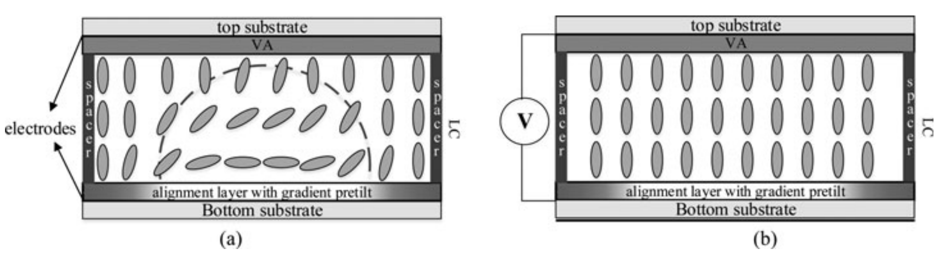

Figure 3. Liquid crystal lens structure: (a) no voltage and (b) on-state.

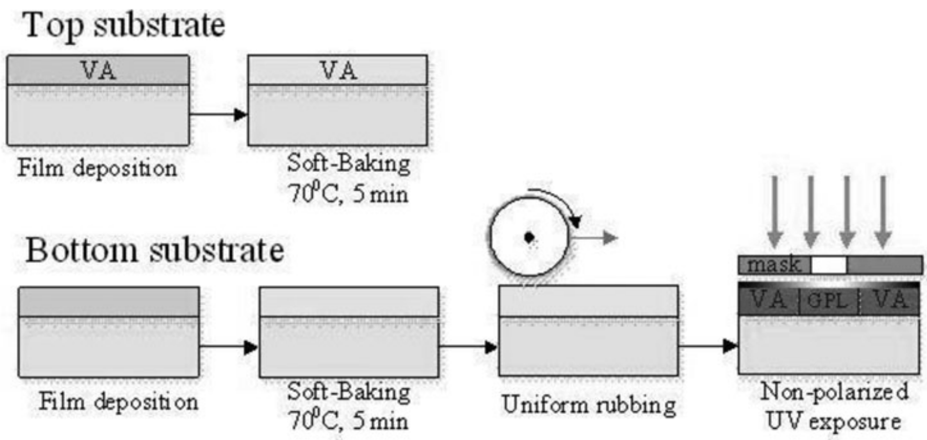

Figure 4. Process flow of alignment layers fabrication for liquid crystal lens.

The process flow of the alignment layers fabrication is presented on Fig. 4. The uniform layer on top substrate (I) has been made in two steps: (I-1) wet deposition and (I-2) soft-baking to remove residual solvent. The bottom alignment layer (II) is processed in four steps: (II-1) wet deposition, (II-2) soft-baking to remove the solvent, (II-3) rubbing to induce the azimuthal alignment direction, and (II-4) UV exposure to induce the polar direction (pretilt angle).

Alignment material at the bottom substrate was irradiated via hole pattern photomask with air gap contact. The light intensity distribution at the alignment layer induced the decrease of pretilt angle from 90° (vertical) to almost 0° (planar alignment). Optimization of exposure conditions resulted in controllable pretilt angle gradient formation required for LC lens. The substrates were assembled into the cell with cell-gap 20 μm and filled with liquid crystal material E7.

4. Examination of the LC lens

To examine the LC lens, the sample has been set between two crossed polarizers. The rubbing direction of the bottom substrate was oriented at 45° to both polarizers. Figure 5 shows

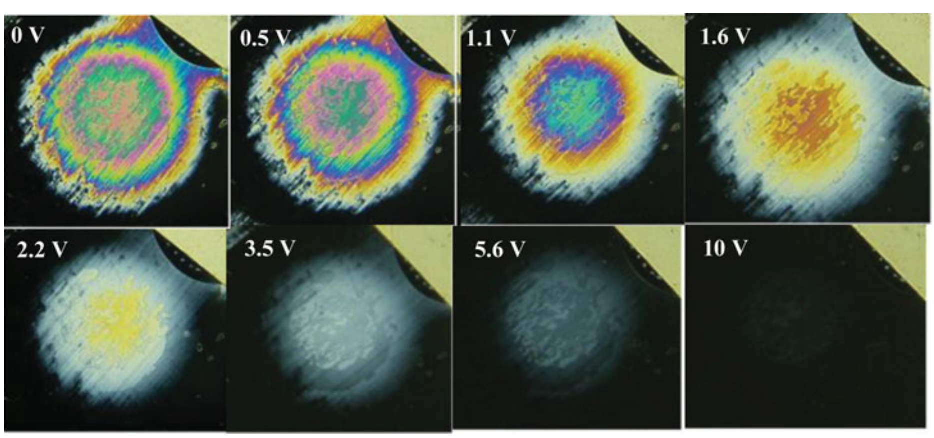

Figure 5. Photographs of LC lens sample with different applied voltages placed in between crossed polarizers at 45° to the rubbing direction.

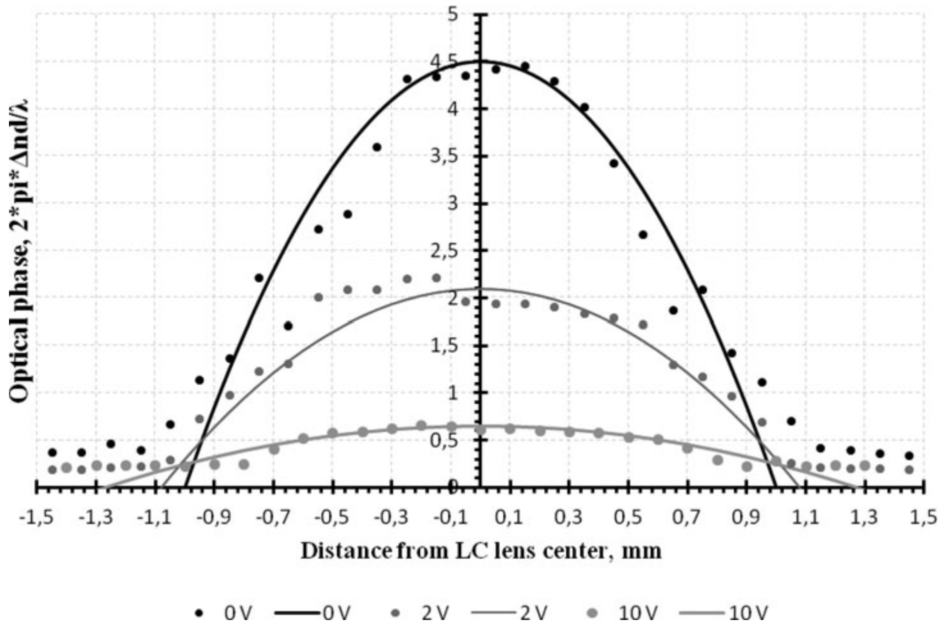

Figure 6. Phase difference distribution in the liquid crystal lens structure.

photographs of the LC lens with different voltage levels applied, taken by a microscope camera.

The photomask hole pattern diameter of 1.5 mm yields LC lens diameter ∼2 mm (Fig. 6). The measured phase profile of the LC lens is shown with dots. The corresponding parabolic approximation of the lens profile is given with solid lines. Obviously, voltage of 10 V AC 1 kHz is sufficient to switch the liquid crystal into vertical state and almost completely convert the inhomogeneous distribution of optical phase difference into uniform one (corresponds to the lens with infinite focal length). Consequently, the operation voltage levels of the obtained LC lens for tunable focal length are below 10 V.

It is easy to show that the focal length of the LC lens F is given by the following expression:

$$F = \frac{R^2 - (\Delta nd)^2}{2\Delta nd},$$

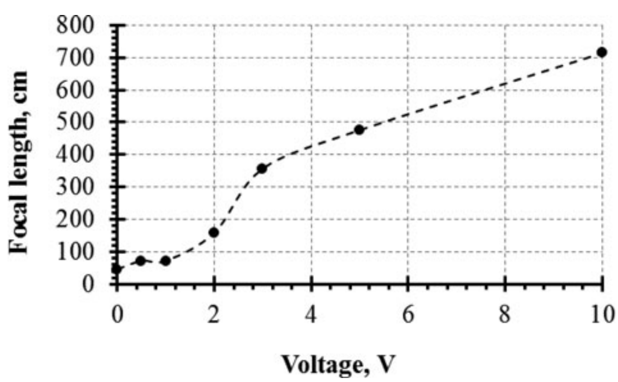

Figure 7. Focal length F dependence on applied voltage.

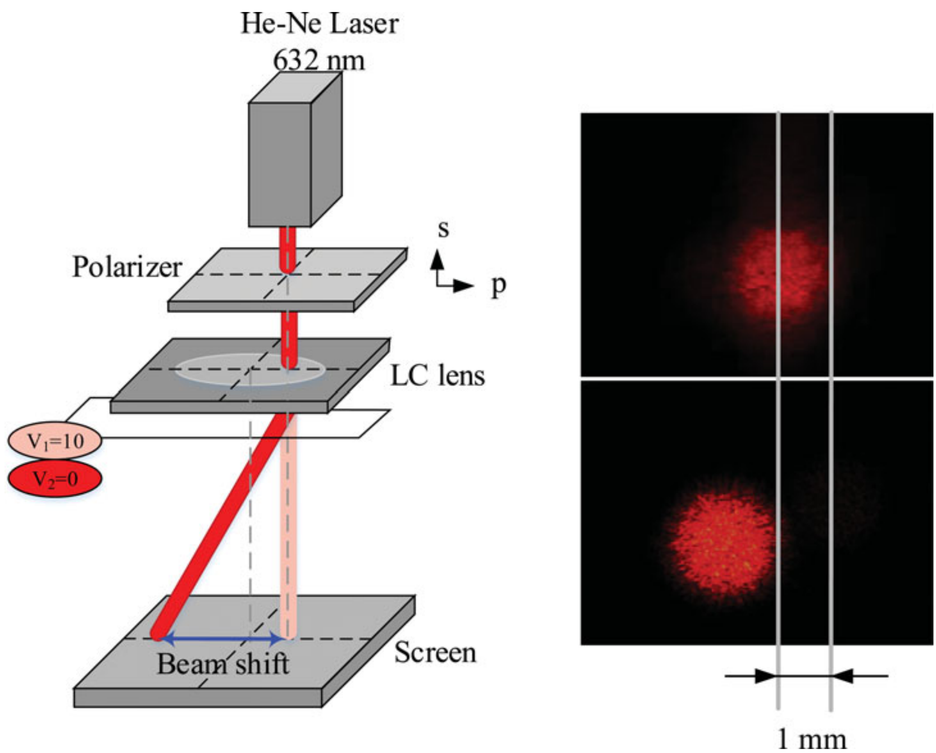

Figure 8. Light beam propagation scheme and photograph of the screen with the beam shift at LC lens operation.

where R is radius of lens, Δnd is phase retardation. The values of F calculated for various voltages are presented in Fig. 7.

According to Fig. 7 the focal length of the obtained LC lens is tunable from 47 cm to more than 700 cm by applying voltage in the limits of 0–10 V. Reduction of the LC lens radius R and utilization of liquid crystal materials with larger birefringence, Δnd is the way to shorter focal lengths.

To observe the operating mode of LC lens we put laser beam on the edge of the lens (Figs. 8 and 9) and the beam bends at the lens interface, while on having applied voltage the beam passes straight. The distance from the lens to the screen equals to 80 cm and lens diameter 2 cm.

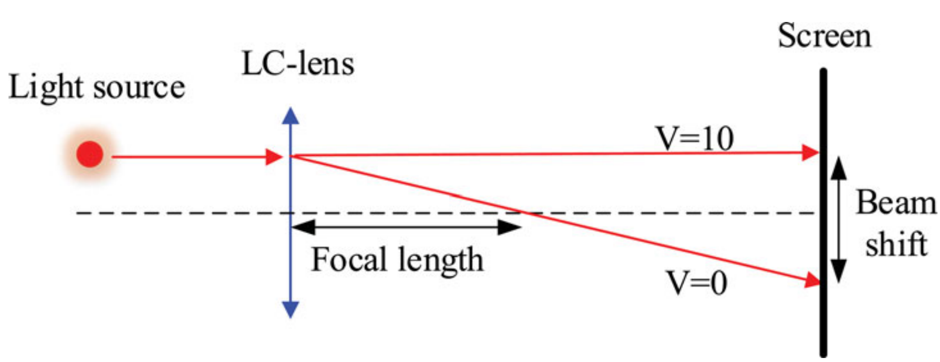

Figure 9. Ray diagram of beam shift at LC lens operation.

5. Conclusion

A new fabrication technique of liquid crystal lenses based on the novel liquid crystal alignment material with pretilt angle gradient was developed. Required distribution of the pretilt angle on the surface of the alignment layer is formed due to two-stage processing: uniform rubbing and inhomogeneous nonpolarized UV exposure. It creates bell-shaped distribution of LC birefringence in the cell with uniform cell-gap forming the lens with minimal focal length in off-state. Voltage levels within 0–10 V range tune the focal length of the LC lens with diameter ~2 mm from 47 to 700 cm, correspondingly. The fabrication method is scalable to lens arrays with only two control electrodes for 2D/3 D autostereoscopic and light-field displays.

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