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Abstract. We describe a simple but very efficient optical device that allows the dynamic focusing of unpolarized light using a single-nematic liquid crystal layer. The operation principle of the proposed device is based on the combination of an electrically variable “half-lens” with two fixed optical elements for light reflection and a 90-deg polarization flip. Such an approach is made possible thanks to the close integration of the thin film wave plate and mirror. Preliminary experimental studies of the obtained electrically variable mirror show very promising results. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: 10.1117/1.OE.54.2.025104]

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1 Introduction

Mobile miniature cameras are undergoing continuous growth of complexity and, at the same time, are under very strong cost reduction pressure.¹ One of the highly desired features of such cameras is the autofocus function required for bar code or text scanning. Today, the widely accepted approach, enabling the autofocus, is based on the use of the axial mechanical movement of the camera's base lens with the help of voice coil motors (VCMs). Despite the dominating position, this technology has several drawbacks such as the tilt and gravity sensitivities, as well as limited possibilities for further miniaturization and cost reduction. This explains the emergence of alternative approaches, such as liquid² or elastomeric³ lenses, based, respectively, on the deformation of an interface between two immiscible liquids and on the deformation of an elastomer. While those approaches are very elegant and polarization insensitive, they still suffer from several drawbacks: the necessity of hermetic packaging and the associated high-manufacturing cost are probably the most important aspects here.

At the same time, most of the thermotropic liquid crystalline (LC) materials^{4,5} are hydrophobic and do not require such precautions. Their technical performance and excellent environmental robustness were already demonstrated by the LC display (LCD) application.⁶ Many approaches have been demonstrated to also build nematic LC (NLC) components for optical imaging.^{1,7–17} However, those materials have a fundamental limitation: they are polarization sensitive since the refractive index modulation here is achieved by the electrical field-induced reorientation of their local anisotropy axis (commonly called “director,” representing the local average direction of the long molecular axes of the NLC⁴). Figure 1(a) schematically demonstrates an electrically variable NLC lens using a single-layer of NLC that is in the Y, Z plane (with its ground state director being parallel

with the Y -axis). The application of the external nonuniform excitation (e.g., electrical field; see various methods of generating such nonuniform excitation in Refs. 1 and 7–17) may generate a lens-like orientational distribution of the director across the Y, Z plane, while the director [shown as short bars in Fig. 1(a), confined in the NLC layer] remains mainly in the X, Y plane. Such a reorientation may generate, for example, a spherical phase delay to create a lens, similar to a gradient index (GRIN) lens, the refractive index profile of which may be expressed as (see, e.g., Ref. 1)

$$n_{\text{GRIN}}(r) = n_c - r^2/(2fL), \quad (1)$$

where r , f , L , and n_c are the radial distance (from the center of the lens), focal length of the lens, the LC layer's thickness, and the refractive index at the center of the lens, respectively. The local value of n_{GRIN} is defined by the local birefringence Δn of the used NLC as well as the angle of the director with respect to the light wavevector k_i (see, e.g., Ref. 18). Such a lens may provide an electrically variable optical power (OP)¹ that may be approximately expressed as

$$\text{OP} = 2\delta nL/r_m^2, \quad (2)$$

where the OP is expressed in diopters ($D = \text{m}^{-1}$), δn is the effective (see hereafter) birefringence (always $\leq \Delta n \equiv n_{\parallel} - n_{\perp}$, with n_{\parallel} and n_{\perp} being, respectively, the refractive index values of the NLC for extraordinary and ordinary polarization modes of light), r_m is the half of the clear aperture diameter of the lens, and L is the thickness of the NLC layer.

However, such a lens may focus only the E_y polarization (extraordinary) component of the normally incident light (with the wavevector k_i) since, during the operation of the lens, the director of the NLC layer remains in the X, Y plane. Thus, the orthogonal (ordinary) polarization component E_z of light will exit from the NLC layer with a uniform phase delay and thus will not be focused. This is the reason

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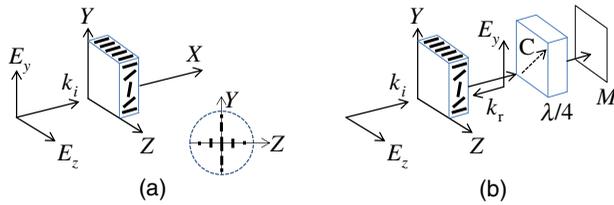


Fig. 1 (a) Schematic demonstration of the operation of a single-layer of NLC as an electrically variable lens of positive optical power. The short bars represent the director of the NLC. k_i is the wave vector of the incident light with two perpendicular polarization components, E_y and E_z . The circular inset represents the top view of projections of the director in the Y, Z plane. (b) Forward (k_i) and backward (k_r) propagations of the original Z polarization component of light in the proposed electrically variable mirror. A quarter wave plate ($\lambda/4$) and mirror (M) are used to insure the polarization-independent operation.

why this single-layer lens may be called a “half-lens,” since it can only focus half of the unpolarized light.

Indeed, almost all practical solutions for lenses (intended to work with unpolarized light, e.g., sun light) would require the fabrication of “full” lenses with two NLC layers having perpendicular orientations of their directors (e.g., the director of the first layer being in the X, Y plane, while the director of the second layer being in the X, Z plane) to focus the unpolarized light propagating in the X direction [Fig. 1(a)]. Those NLC layers must be positioned very closely and must perform in a similar way to avoid focusing two polarization components (E_y and E_z) of the incident light (with wavevector k_i) in close focal points on the X -axis. Otherwise, additional image quality degradation or “polarizational aberrations” would be generated.

To the best of our knowledge, the only single-layer LC-based alternative approach in an effort to simplify the manufacturing of such lenses, was the use of LC materials in the so called blue phase.¹⁹ This is a phase that may be macroscopically considered as isotropic in the ground state, which, however, undergoes anisotropic refractive index changes when subjected to an external electrical field. In this case, the refractive index modifications may be similar for two orthogonal polarization components of light at normal incidence on the LC cell. While the use of a single LC layer (along with a very fast response time and the absence of alignment layers) is a very attractive feature, the required voltages here (to operate the lens) are much higher (≈ 70 V) and the obtained lens still demonstrates polarization dependence at larger incidence angles.

2 Proposed Solution

At the same time, to increase the viewing angle performance of LCDs, transparent solid broadband anisotropic layers have been recently introduced using liquid reactive mesogen (RM) materials, which are aligned as NLC materials and then are polymerized to obtain thin polymerized RM (PRM) solid films. In the present work, we propose a simple, but very efficient solution to the above-mentioned polarization dependence problem by using the well-known “quasi-isolation” scheme using a PRM quarter wave plate. Namely, we propose to combine a single NLC layer with a very thin layer of such an anisotropic layer of PRM to build a light focusing element [electrically variable liquid crystal mirror (EVLCM)], which may be polarization insensitive. The

operation of the proposed EVLCM is based on the broadband polarization flip (rotation at 90 deg) of the reflected light. Before describing the basic concept, let us emphasize that the thin and integrated character of the PRM is key in this application (see hereafter). The basic geometry of this component is schematically demonstrated in Fig. 1(b). The ground state director of the NLC is parallel to the Y -axis. Here also, during the operation of the EVLCM, the director of the NLC layer remains in the X, Y plane. The anisotropic PRM layer is built to perform as a broadband quarter wave plate ($\lambda/4$). Its anisotropy axis C is aligned at 45 deg with respect to the Y -axis. For simplicity, only one original (initial) polarization component (ordinary, E_z) of the incident light is shown. This component (light is incident from the left) will exit from the NLC layer with a transversally uniform phase front (and thus without focusing). However, it will further traverse the quarter wave plate ($\lambda/4$), will be reflected from the mirror M, and will traverse the same quarter wave plate ($\lambda/4$) for a second time, but in the opposite direction. This double passage will rotate its polarization at 90 deg. Thus, the obtained beam will enter (from the right) into the NLC layer as an extraordinary polarized light (along the Y -axis). In this case, a lens-like phase front modulation (and focusing) will be generated by the NLC layer. Obviously, the perpendicular initial polarization component E_y of the incident light (from the left) will be focused on its first passage through the NLC layer and will not undergo further focusing during its second passage (from the right), since then it will have ordinary polarization.

While the combination of a quarter wave plate with a reflecting element has already been used, the current solution is using the very thin and closely integrated characters of PRM and thin film mirror technologies to insure that the effective two focusing NLC layers are virtually very close to each other. Otherwise, the proposed tunable mirror would have unacceptable aberrations (see below).

3 Experimental Conditions and Results

To validate the proposed scheme, we have used a half-lens provided by LensVector (see, e.g., Ref. 1). Its clear aperture was $\varnothing \approx 2.5$ mm, the optical birefringence of the NLC used (homemade mixture) was $\Delta n = 0.2$, and the thickness L of the planar oriented [thanks to polyimide (PI) layers] NLC was $50 \mu\text{m}$. The lens used a well-known “modal control” scheme,^{1,8} where the bottom and top substrates of the cell are coated, respectively, by uniform and hole-patterned (HP) indium tin oxide (ITO) electrodes (Fig. 2). The uniform

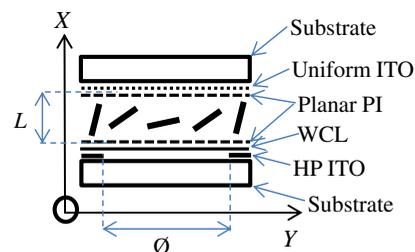


Fig. 2 Schematic demonstration of the cross-sectional structure of the electrically variable liquid crystal half-lens. The liquid crystal director (shown as short bars) is reoriented in a nonuniform way thanks to the corresponding electrical field generated by the combination of the uniform ITO and the hole-patterned ITO (HP ITO). The last one is covered by the weakly conductive layer (WCL).

electrode is ground. The aligned PI layers are rubbed in anti-parallel (180 deg) directions, generating thus an approximate pretilt angle of 3 deg. This pretilt is responsible for the preferable “asymmetric” molecular reorientation when a centrosymmetric electrical field is applied to the cell via the HP ITO (see, e.g., Ref. 20). The smooth lens-like profile of the electrical field (inside the NLC layer) is obtained thanks to the very thin weakly conductive layer (WCL) made of ZnO (coated on the top of the HP ITO) providing several tens of $M\Omega/\square$ sheet resistance. The WCL helps to propagate the electrical potential from the periphery of the HP ITO toward the center of the cell. This softens the electrical field’s profile in the NLC layer and minimizes the optical aberrations. The frequency of the electrical signal, applied to the HP ITO, is changed from 1 kHz (when the electrical field is uniform in the NLC layer and thus the OP of the cell is zero; there is no light focusing) to 5.5 kHz (when the electrical field is noticeably reduced in the center of the cell compared with the periphery and thus the NLC’s reorientation is lens-like and the cell focuses light). It may be useful to mention that, at 1 kHz, the driving electrical field is not only uniform (thanks to the WCL), but also perpendicular to the cell substrates. In this case, thanks to the above-mentioned pretilt, the angle between that electrical field and the ground state molecular orientation is the same everywhere in the cell. Consequently, the electrical field-induced molecular reorientation is performed in one direction everywhere in the cell (from the Y -axis, Fig. 2 toward the X -axis). When the frequency of the electrical field is continuously increased up to 5.5 kHz, the field becomes nonuniform and curved. The molecular reorientation is adapted correspondingly, while still keeping the asymmetric (Fig. 2) reorientation and avoiding the orientational defects (this is the so-called “frequency tuning” concept of LensVector Inc.²¹).

The experimental setup used for the characterization of the electrically variable mirror is described in Fig. 3. An unpolarized CW He-Ne laser (operating at 632.8 nm) beam was used as probe. A telescopic system was used to adjust the diameter of the beam (>3 mm). A polarizer (mounted in a rotating frame) was used to choose the desired initial polarization of the probe. A polarization-insensitive beam splitter (BS) was used to forward the reflected, from the EVLCM, light toward the Shack–Hartmann wave front

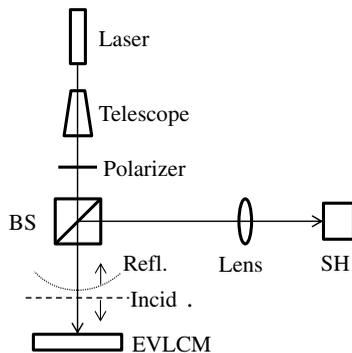


Fig. 3 Schematic demonstration of the experimental setup used for the study of the operation of the electrically variable liquid crystal mirror (EVLCM). Laser: CW He-Ne operating at 632.8 nm, Telescope: optics used to adjust the diameter of the beam, BS: polarization-insensitive beam splitter, SH: Shack–Hartmann wave front sensor, and Incid. and Refl.: incident and reflected wave fronts, respectively.

sensor (SH), purchased from ThorLabs. An additional fixed lens (with $F = 15$ cm focal length, positioned at a $2F$ distance from the sample and the SH) was used to image the output (the same as the input) plane of the EVLCM on the input of the SH. The incident planar and reflected spherical wave fronts are shown as Incid. and Refl., respectively.

The experimental procedure was as follows. The wave front of the reflected, from the EVLCM, light for a given input initial polarization (ordinary or extraordinary) was studied at different electrical excitation values, generating various wave front curvatures and corresponding OPs. Simultaneously, the root mean square (RMS) wave front errors (in micrometers) were also measured for each OP. Then, the direction of the initial polarization was rotated for 90 deg (by the polarizer) and the same experiment was conducted again.

The obtained preliminary (nonoptimized) results are presented in Fig. 4. As we can see, the variation of the electrical excitation frequency (typical control mode for LensVector lenses; using alternative current sinusoidal-shaped electrical signal with an RMS amplitude of 6.4 V) allows the gradual change of the OP (in diopters) of the EVLCM [squares; on the left vertical axis of Fig. 4(a)]. At the same time, we can observe a corresponding change of RMS aberrations (circles, right vertical axis). We can also notice some undesired differences of OPs for the cases of initial polarizations being parallel (filled squares) or perpendicular (open squares) to the ground state director of the NLC. There is also a relatively small difference of the RMS aberrations for corresponding polarization components (parallel—filled circles and perpendicular—open circles) of the probe. Figure 4(b) shows the three-dimensional picture of a typical wave front detected by the SH sensor.

4 Discussions

We can first use the lens parameters and Eq. (2) to determine the theoretical limit of the possible maximum achievable OP. It appears to be $OP = 12.8D$. The maximum OP obtained in our experiments was approximately 30% less, which is not surprising since the effective optical path difference (OPD) in an NLC layer is typically given by the equation

$$OPD = (2\pi/\lambda_0) \int_0^L \delta n(x) dx, \quad (3)$$

where the $\delta n(x) = n_e(x) - n_o$ is the local value of the effective birefringence (the difference between the refractive indices of ordinary and extraordinary polarization modes), which changes with the propagation of light along the X -axis. As we have already mentioned, this value is always $\leq \Delta n$, since the molecular reorientation is nonuniform in the NLC cell (more in the center of the cell than close to its substrates).

A more important aspect of the experimentally obtained results is the mismatch of OPs for two perpendicular polarized modes [Fig. 4(a)]. As can be seen, the OP difference is less than $\pm 1D$ at 8.5D of OP (at 5.25 kHz of driving frequency). This is not so bad given the fact that, to form an image, such a mirror must be combined with a fixed focus lens of 250D to 300D of OP. However, we have performed some additional studies (not reported here) that have shown that the undesired residual polarization dependence was caused by our homemade PRM film. Indeed, it appeared

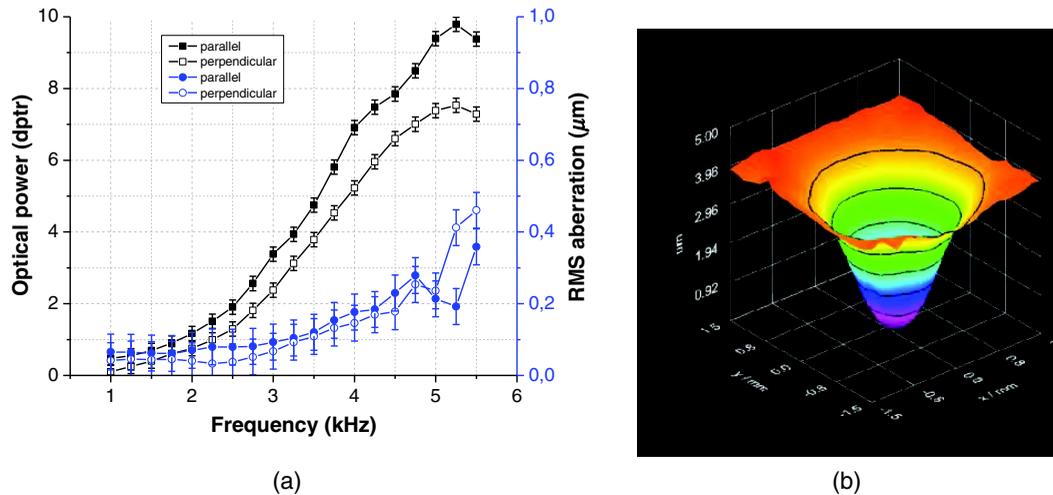


Fig. 4 (a) Dependences of EVLCM's OP (squares) and RMS aberrations (circles) upon the frequency of the applied voltage. Filled symbols correspond to the polarization of the initial beam that is parallel to the ground state director, while the open symbols correspond to the initial perpendicular polarization component of the incident beam. (b) Typical three-dimensional wave front of the probe beam detected by the SH wave front sensor. The incident beam's polarization is parallel to the ground state director.

that the film was not performing exactly as a quarter wave plate and the generated relative phase delay $\Delta\varphi = 2\pi\delta n_{\text{PRM}}L/\lambda$ (where δn_{PRM} , λ , and L are the values of the PRM's anisotropy, the light wavelength in vacuum, and the thickness of the PRM, respectively) was slightly different from $\pi/2$. Thus, the desired 90-deg rotation was not performed accurately and some ellipticity of backpropagating light polarization was generated. Thus, a part of the light (initially of ordinary polarization) was not focused and the SH sensor interpreted this as a lower OP (open squares) and higher aberrations (open circles) [Fig. 4(a)].

For the same reasons (the PRM film is not yet optimized), we did not study the angular properties of our homemade quarter wave plate. Such a study would be necessary to evaluate the possible angular dependences of the value of $\Delta\varphi$ and its influence on the angular performance of the proposed mirror when it would be integrated in various optical imaging systems. However, for practical reasons, we prefer to use commercial polymeric quarter wave plates, which are presently fabricated in large volumes for the roll-to-roll fabrication of displays by many manufacturers (e.g., JX Nippon Oil & Energy Corporation). At the same time, thin film reflection or antireflection coatings are already used in large window applications. Both of those components are thus well mastered and have low cost.

We think that the proposed mirrors may be used in both optical autofocus and zoom in the architectures applying light reflection (at least one of the mirrors being the EVLCM proposed here). Indeed, today's cameras (sometimes 6 units per mobile phone!) are continuously shrinking in size having lateral sizes of $5\text{ mm} \times 5\text{ mm}$, which enable their use when the camera is aligned with its optical axis parallel to the main screen of the mobile device (the typical thickness of which is about 10 mm). Referring to Fig. 1(b), the EVLCM may be designed to operate at 45 deg and thus the incident light (along the X-axis) may be reflected, e.g., first in the $-Y$ direction and then in the $-Z$ direction, to form the image. It might be important to notice that such sizes almost exclude the use of VCM technology to implement

advanced functionalities (too difficult to further miniaturize), while the LC lenses and mirrors may be used in even smaller architectures.

5 Conclusion

Thus, we can already say that the proposed solution may be used for many telescopic optical schemes. So, despite the above-mentioned missing elements, we think that the proposed element is very promising for multiple points of views. First of all, it uses a single NLC layer to focus unpolarized light, which greatly simplifies the manufacturing process and thus reduces the cost of the element. Second, the PRM layer and the mirror may be built (coated) directly on the internal surface of the NLC cell's back substrate, providing a minimal distance D between the two "effective" NLC layers that may be reduced to approximately $D \approx 50\text{ }\mu\text{m}$. Let us note that in "traditional" lenses (using two crossed half-lenses) this distance is defined by the double of the cell substrate thickness (ranging from several hundreds of micrometer to millimeter) at least. Finally, the required voltages here are an order of magnitude lower compared with blue-phase LCs and the NLCs used here are better mastered at the industrial level.

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References

1. T. Galstian, *Smart Mini-Cameras*, CRC Press, Taylor & Francis Group, Boca Raton (2013).
2. B. Berge and J. Peseux, "Variable focal lens controlled by an external voltage: an application of electrowetting," *Eur. Phys. J. E* **3**, 159–163 (2000).
3. P. Liebetraut et al., "Elastomeric lenses with tunable astigmatism," *Light: Sci. Appl.* **2**, e98 (2013).
4. P. G. de Gennes and J. Prost, *The Physics of Liquid Crystals*, 2nd ed., Oxford University Press, Oxford (1995).

5. L. M. Blinov and V. G. Chigrinov, *Electrooptic Effects in Liquid Crystal Materials*, Springer, New York (1994).
6. P. Yeh and C. Gu, *Optics of Liquid Crystal Displays*, Wiley, New York (1999).
7. F. J. Kahn, "Electrically variable iris or stop mechanisms," US 3,741,629 (1971).
8. A. F. Naumov et al., "Control optimization of spherical modal liquid crystal lenses," *Opt. Express* **4**(9), 344–352 (1999).
9. S. Sato, "Applications of liquid crystals to variable-focusing lenses," *Opt. Rev.* **6**(6), 471–485 (1999).
10. H. Ren et al., "Tunable-focus flat liquid crystal spherical lens," *Appl. Phys. Lett.* **84**(23), 4789–4791 (2004).
11. V. V. Presnyakov et al., "Tunable polymer-stabilized liquid crystal microlens," *Opt. Express* **10**(17), 865–870 (2002).
12. N. A. Riza and M. C. Dejule, "Three-terminal adaptive nematic liquid-crystal lens device," *Opt. Lett.* **19**(14), 1013–1015 (1994).
13. J. Knittel et al., "Liquid crystal lens for spherical aberration compensation in a blu-ray disc system," *IEE Proc. Sci. Meas. Technol.* **152**(1), 15–18 (2005).
14. L. Li et al., "Speed, optical power, and off-axis imaging improvement of refractive liquid crystal lenses," *Appl. Opt.* **53**(6), 1124–1131 (2014).
15. M.-C. Tseng et al., "Tunable lens by spatially varying liquid crystal pretilt angles," *J. Appl. Phys.* **109**, 083109 (2011).
16. H.-C. Lin and Y.-H. Lin, "An electrically tunable-focusing liquid crystal lens with a low voltage and simple electrodes," *Opt. Express* **20**(3), 2045–2052 (2012).
17. K. Asatryan et al., "Optical lens with electrically variable focus using an optically hidden dielectric structure," *Opt. Express* **18**(13), 13981–13992 (2010).
18. P. C.-P. Chao, Y.-Y. Kao, and C.-J. Hsu, "A new negative liquid crystal lens with multiple ring electrodes in unequal widths," *IEEE Photonics J.* **4**(1), 250 (2012).
19. C.-Te Lee et al., "Design of polarization-insensitive multi-electrode GRIN lens with a blue-phase liquid crystal," *Opt. Express* **19**(18), 17402–17407 (2011).
20. O. Pishnyak, S. Sato, and O. D. Lavrentovich, "Electrically tunable lens based on a dual-frequency nematic liquid crystal," *Appl. Opt.* **45**(19), 4576–4582 (2006).
21. T. Galstian et al., "Autofocus system and method," US Patent 8,629,932 (2014).

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