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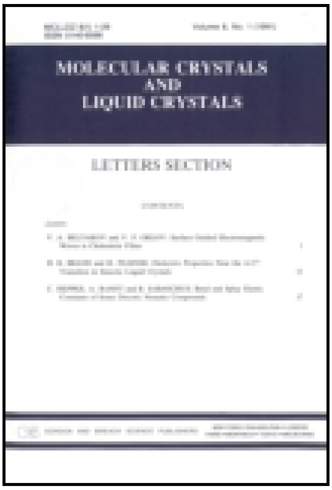

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Electrically Tunable Liquid Crystal Lenses and Applications

Yi-Hsin Lin[a], Hung-Shan Chen[a] & Ming-Syuan Chen[a]

[a] Department of Photonics, National Chiao Tung University, Hsinchu, Taiwan

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Electrically Tunable Liquid Crystal Lenses and Applications

YI-HSIN LIN,* HUNG-SHAN CHEN,
AND MING-SYUAN CHEN

Department of Photonics, National Chiao Tung University, Hsinchu, Taiwan

Electrically tunable liquid crystal (LC) lenses have been studied for over 30 years. Three main problems of LC lenses hinder the applications: 1) the paradox between the response time and tunable focusing range, 2) polarization dependency, and 3) large aperture size for ophthalmic lenses. In this paper, we introduce the two mode switching method of the LC lenses to solve the paradox of the LC lenses. The basic optical principles for designing polarization independent LC lenses are discussed and several polarizer-free LC lenses we developed are reviewed. Several applications of LC lenses are also introduced, including auto-focusing imaging systems, auto-focusing projection systems, optical zoom systems, endoscopic systems, solar cells, ophthalmic lenses for myopia-presbyopia.

Keywords Liquid crystal lenses; tunable focusing properties; LC lenses

1. Introduction

Lenses are the fundamental elements in optical systems and photonic related applications. In the conventional imaging systems, many lenses are required for different purposes and the distances between lenses are usually required to move mechanically. The imaging systems are too bulky and heavy. Electrically tunable focusing lenses provide solutions to reduce the size and volume of the optical systems for many applications. Liquid crystals (LCs) modulate the light in optical amplitude and optical phase because of the optical anisotropy and dielectric anisotropy of liquid crystals. LC is a good candidate for designing electrically tunable focusing lenses [1–2]. In this paper, the general design principles of LC lenses are discussed. We categorize the LC lenses by the spatial phase difference. We show the three main challenges of the LC lenses and the related solutions. The applications of LC lenses are also introduced.

2. General Design Principles

The function of a "lens" is to convert a plane wave to a converging or diverging spherical wave based on spatial phase difference of an optical medium. The general description of spatial phase difference (Γ(r)) can be expressed as:

$$\Gamma(r) = \frac{2\pi}{\lambda} \times \delta[n \times d], \qquad (1)$$

*Address correspondence to Y. H. Lin, Department of Photonics, National Chiao Tung University, Hsinchu, Taiwan 30010, R.O.C. Tel.: +886-3-5712121 ext 56376; Fax: +886-3-5737801; E-mail: yilin@mail.nctu.edu.tw

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where r is the position, λ is wavelength, d is thickness, n is refractive index of the optical medium, and represents the variation. Eq. (1) can be further extended as shown in Eq. (2).

$$\Gamma(r) = \frac{2\pi}{\lambda} \times [n \times \delta d(r) + \delta n(r) \times d + \delta n(r) \times \delta d(r)]. \quad (2)$$

Assume that the distribution of the spatial phase difference is parabolic. $\Gamma_{b,c}$ represents the spatial phase difference between the center and the border (or periphery) of the lens with a radius of r_0. The focal length (f) of the lens is [1–3]:

$$f = \frac{\pi \times r_o^2}{\Gamma_{b,c} \times \lambda}. \quad (3)$$

When the refractive index is a constant (n), the lens shape should be parabolic and the focal length is contributed from the variation of thickness which is: $f = r_o^2/[2 \times (n-1) \times (d_c - d_b)]$. d_c and d_b are the thickness at the center and the thickness at the border (or periphery) of the lens, respectively. When the thickness of the lens is a constant (d), the distribution of the refractive index of the lens should be parabolic and the focal length is: $f = r_o^2/[2 \times d \times (n_c - n_b)]$. n_c and n_b are the refractive indices at the center and at the border (or periphery) of the lens, respectively. By properly arranging the spatial phase difference, we can realize the lenses with different focal lengths and the image qualities (abberations).

We can categorize the LC lenses by three types of spatial phase difference according to Eq. (1). The first one is the type of the inhomogeneous thickness of the LC layer with a spatially homogeneous distribution of refractive indices, and the spatial phase difference is $\Gamma(r) = 2\pi/[\lambda \times n \times \delta d(r)]$. The general illustration is depicted in Fig. 1(a) and Fig. 1(b). In this type, the structure usually consists of a curved glass substrate and a layer of LC filled between glass substrates coated with alignment layers and ITO electrodes. The focal length (f_1) is contributed by two parts: the curved substrate with a fixed focal length (f_g) and the LC layer with voltage (V) depending on focal length ($f_{LC}(V)$). f_1 equals $[1/f_{LC}(V) + 1/f_g]^{-1}$. The function of the LC layer is to electrically change the refractive index ($n_{eff}(V)$). Assume the radius of curvature of the glass substrate is R. $f_{LC}(V)$ then equals $R/[n_{eff}(V) - 1]$. In Fig. 1(a) and Fig. 1(b), when a light passes through a sheet polarizer with the transmissive axis parallel to the rubbing direction of the LC layer, the focal length of the LC lens changes with the applied voltage due to the orientations of LC directors. Many literatures reported the structures of the LC lenses belong to this category [4–9]. However, the inhomogeneous

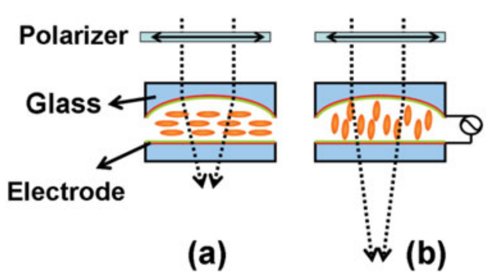

Figure 1. Typical LC lenses with the inhomogeneous thickness of the LC layer and a spatially homogeneous refractive indices at (a) a voltage-off state and (b) a voltage-on state.

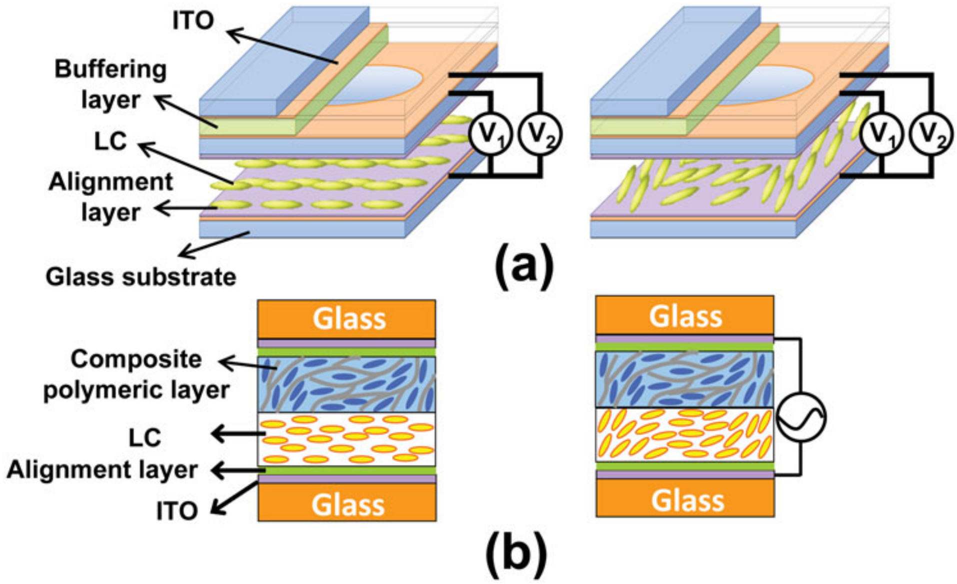

Figure 2. Typical LC lenses with an inhomogeneous distribution of refractive indices and a uniform thickness of a LC layer. (a) The typical structure of a LC lens with a hole-patterned electrode. The left figure in (a) is at voltage-off state and the right figure of (b) is at voltage-on state. ($V_1 > V_2 > V_{th}$) (b) The structure of a LC lens without hole-patterned electrode. The left figure of (b) is at voltage-off state and the right figure of (b) is at voltage-on state. The inhomogeneous electric field applied to LC layers results from an inhomogeneous distribution of relative permittivity of the composite polymeric layer. The composite polymeric layer also has a fixed focal length.

thickness of the LC layer causes the non-uniform response time and the scattering when the variation of the thickness is large.

The second type of the LC lenses is the inhomogeneous distribution of refractive indices with a uniform thickness of a LC layer and the spatial phase difference is $\Gamma(r) = 2\pi / [\lambda \times \delta n(r) \times d]$. The typical structure is illustrated in Fig. 2(a) [10–23]. This type is so-called gradient index lens (GRIN lens). The lensing effect results from the spatial distribution of the refractive indices owing to the orientations of LC directors. A LC layer and a dielectric layer are sandwiched between two electrodes. The function of the middle glass substrate (dielectric layer) is to enlarge the aperture size (>1 mm) of the LC lens. The dielectric layer can be a glass substrate, a highly resistive layer, a composite dielectric layer, or a composite polymeric layer [22–23]. The electrodes are usually patterned with a hole to generate inhomogeneous electric field to the LC layer. Fig. 2(b) shows a LC lens without hole-patterned electrode. In Fig. 2(b), the composite polymeric layer with a distribution of dielectric constant (i.e. relative permittivity) helps to generate the inhomogeneous electric field to the LC layer and provide extra-lens power to shift the lens power of the whole LC lens; meanwhile, the composite polymeric layer also provide the alignment capability to the LC layer [22–23]. The advantage of this type is easy to fabricate. The disadvantage is the operating voltage is usually high. To reduce the voltage, a highly resistive layer is preferred; however, the frequency dependent properties cause the requirement of the temperature controller of the LC lenses. In addition, the disclination lines affecting the image quality need to be avoided by properly arranging the electric fields. Using pixilated

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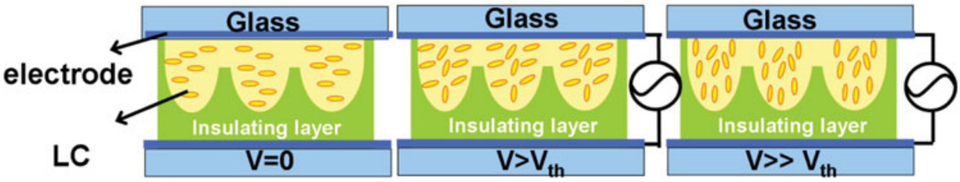

Figure 3. Typical LC lenses with spatially inhomogeneous refractive indices and a spatially inhomogeneous thickness of a LC layer at V = 0, $V > V_{th}$, and $V >> V_{th}$.

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ITO electrodes to generate inhomogeneous electric fields to the LC layer is also a way to realize LC lenses. However, the non-smooth phase profile resulting from the electrode gaps between electrodes affects image quality. The requirement of this LC lens is to use very high resolution of electrode pixels [1, 49]. Recently, Li et. al. proposed a driving scheme based on floating electrodes to improve the image quality [50].

The third type of the LC lenses is the spatially inhomogeneous refractive indices with a spatially inhomogeneous thickness of a LC layer and the spatial phase difference is $\Gamma(r) = 2\pi / [\lambda \times \delta n(r) \times \delta d(r)]$. Fig. 3 illustrates the typical structure of LC lenses. The lensing effect results from the non-uniform cell gap and inhomogeneous electric field which can be achieved by an inhomogeneous insulating layer [21]. Assume the incident light is linearly polarized light. Without a voltage, the focal length is the combination of focusing effects of the insulating layer and the LC layer with a constant refractive index (extraordinary refractive index, n_e). The focal length of the LC lens results from both of the insulating layer and the spatial distribution of refractive indices of the LC layer as the voltage exceeds the threshold voltage (V_{th}). When the voltage is so much larger than V_{th}, the LC directors are perpendicular to the glass substrates and the focal length is the combination of focusing effects of the insulating layer and the LC layer with a constant refractive index (ordinary refractive index, n_o). However, the voltage of this type of LC lenses is usually high and the tunable focusing range is small. Besides those three types, optical diffractive effect can be added to help designing LC lenses. Many literatures reported the LC lenses based on diffractive Fresnel zone plate [24–32]. The aperture size can be large (>1 cm). However, the focal length is not continuously tunable and the diffraction efficiency also limits the application.

As to LC modes, actually all LC modes are able to be adopted for designing a LC lens as long as LC modes can be operated as a pure phase mode, such as nematic LC, cholesteric LC, blue phase LC, polymer networks LC, polymer dispersed LC and so on. In addition, many parameters are related to design a LC lens, such as response times, tunable ranges of lens powers (a lens power is an inverse of the focal length), driving voltages, image performance, aperture size, and polarization dependency. The design parameters are also related to the applications.

3. Challenges and Solutions

The three main challenges of the LC lenses remain: paradox between the response time and tunable range of the lens power, polarization dependency, and large aperture size for ophthalmic lenses. The tunable range of the lens power depends on the cell gap or the thickness of the LC layer. Larger cell gap results in larger phase as well as larger tunable range of the lens power. However, the response time is proportional to the square of the cell gap (or thickness of the LC layers). This means large tunable lens power must result

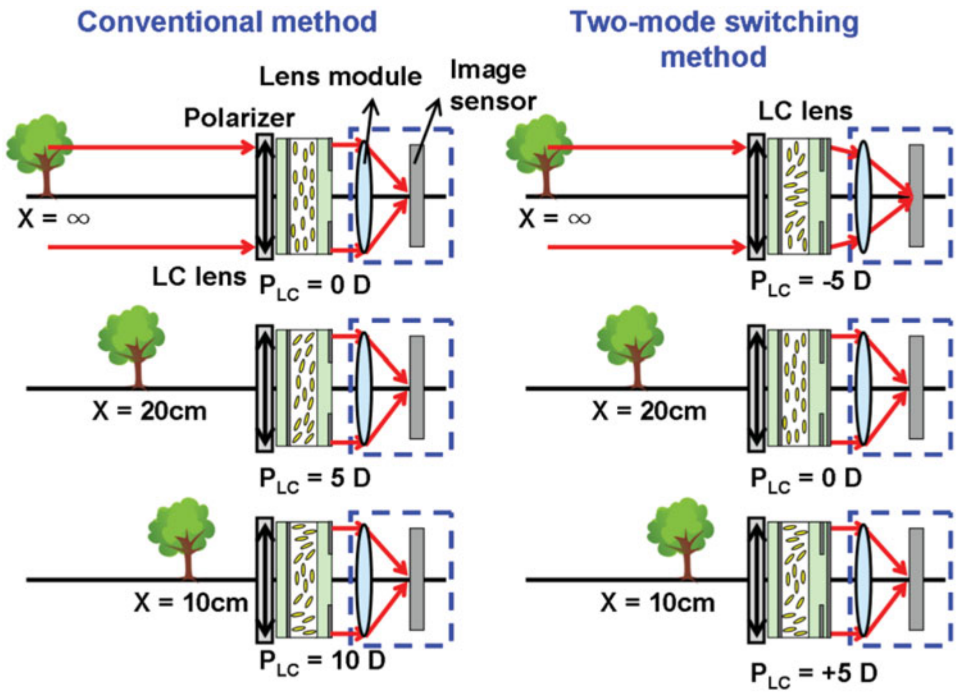

Figure 4. Left: The illustrations of conventional method for operating a positive LC lens in an image system. Right: two mode switching method for operating LC lens as a positive lens and a negative lens in an image system. In both methods, the objective distance in a range from infinity to 10 cm can be imaged clearly at the image sensor.

in slow response time. We take the LC lens with hole-patterned electrodes as an example. When the focal length of the LC lens is tunable from infinity to 10 cm (i.e. tunable lens power is from 0 diopter (D) to 10 D), the cell gap of the LC lens should be larger than 50 μm. Then the response time is slow >30 sec. Such a paradox between the response time and tunable range of the lens power causes the limitation of the applications. To solve the paradox of the LC lens, we proposed the two-mode switching method in 2010 [33]. The illustration to explain two mode switching method and conventional method is depicted in Fig. 4. Conventionally, a LC lens with a polarizer is directly attached to the image system consisting of a lens module and an image sensor located at the focal plane behind the lens module. Assume the object is imaged clearly by such an image system when the object is located within a range from infinity to 10 cm away from the LC lens. The LC lens has to be operated as a positive lens with the lens power switched from 0 D for the object at infinity to 10 D for the object at 10 cm. In this way, the cell gap of the LC lens has to be large (>50 μm) and the response time is slow (>30 sec). To maintain the tunable range of the lens power (10 D in total) and reduce the response time of the LC lens (<1 sec), the LC lens is operated as two modes: a positive lens and a negative lens. The lens power of the LC lens is switched from +5D to −5D. The total tunable range of the lens power is still 10D, but the cell gap is 2x reduced and the response time is 4x improved. The cell gap of the LC lens with conventional hole-patterned electrode is only 25 μm and the response time is 433 ms for imaging the object from infinity to 10 cm. Of course, the response time can be further reduced by electronic driving scheme. By using a different operating method (i.e.

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two mode switching method), the paradox of the LC lens can be solved no matter what kind of structures of LC lens is. As long as the LC lens can be operated as a positive and a negative lens, two modes switching method can help to reduce the cell gap and reduce the response time while maintaining the large tunable range of the lens power [33].

The second challenge of the LC lens is the polarization dependency. The optical properties of the LC materials depend on the polarization of incident light. The requirement of a polarizer reduces the optical efficiency of LC lenses. To remove the polarizer from the LC lenses, the polarizer-free LC lenses have to be developed by developing polarization independent LC phase modulations. Many polarization independent LC phase modulations are proposed in the literatures [34–42]. According to the literatures, we can conclude the general rules to design polarization independent LC phase modulations. The basic principle is that the incident light experiences the same "average" refractive index of LC phase modulators without scattering. Three general rules can be listed as follows. 1) The LC modes should have random orientations of LC directors with the same tilt angle and no scattering. The residual phase modulation belongs to this category [37–39]. The phase is usually small ($<1\pi$ radians) for this phase modulation. 2) We can use two homogeneous LC layers with orthogonal rubbing directions. Each LC layer is in charge of one eigen-linear polarization of light. The double-layered type of LC phase modulations belongs to this category [35–36]. The phase for double-layered type of LC phase modulations is large ($>8\ \pi$ radians), but the phase changes with the oblique angle of the incident light. 3) Use optically isotropic materials for the LC phase modulations, such as blue phase LC(BPLC) [42]. The optical phase of BPLC is small ($\sim 1\pi$ radians), even though the response time is fast (~sub-ms). The performances of polarization-independent phase modulations, such as phase shift, driving voltage and response time, are listed in Table 1. More polarizer-free LC phase modulations still need to be developed for practical applications.

The third challenge is the large aperture size (>10 mm) of the LC lenses for the ophthalmic applications. In order to maintain the uniform thickness of the LC layer for the uniform response time, the inhomogeneous electric fields are applied to the LC layer. When the aperture size of the LC lens is large than 10 mm, the inhomogeneous electric fields of the hole-patterned electrode are difficult to apply to the LC layer for generating the parabolic

Table 1. The list of performance of polarizer-free LC phase modulations [35–42]

Mode	Phase shift ($\Delta\varphi$), radians	Driving voltage	Response time	Ref.
Double-layered LC	8.1π	40 Vrms	τtotal = 300 ms	[35]
Double layered LC gels	1.1π	180 Vrms	τrise = 0.2 ms τdecay = 0.5 ms	[36]
Homeotropic LC gel	0.08π	180 Vrms	τrise = 590 μs τdecay = 150 μs	[37]
PDLC	0.09π	60 Vrms	τrise = 0.8 ms τdecay = 1.9 ms	[38]
PSCT	0.025π	160 Vrms	τrise = 75 μs τdecay = 793 μs	[39]
SP-PDLC	0.1π	40 Vrms	τtotal = 3.8 ms	[40]
T-PNLC	0.28π	30 Vrms	τtotal = 1.6 ms	[41]
PSBP-LC	$1\ \pi$	150 Vrms	τtotal = 3 ms	[42]

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phase profile (or spatial phase difference). In addition, the tunable range of the lens power of the LC lenses needs to be up to 10D for the ophthalmic applications. This means the LC layer needs to be thick (>1 mm) and then the scattering is unavoidable. Diffractive Fresnel zone plate with cholesteric LC can be used to realize the polarizer-free LC lens with large aperture size (~10–20 mm); however, the tunable range is not continuously and the diffraction efficiency limits the applications [24–32]. Another solution is based on double-layered type of LC phase modulations [35–36]. Using a liquid crystal and polymer composite film, the polarizer-free LC lens with a multilayered structure can be realized. The aperture size can be enlarged to >10 mm and the phase increases with the number of layers [45]. However, the fabrication is not easy.

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4. Applications

The LC lenses have many applications, such as the imaging systems of portable devices, pico-projection systems, holographic projection systems, solar cells, ophthalmic lenses for myopia/presbyopia and endoscopic systems [33, 43–48]. In the imaging system, LC lenses can help to realize auto-focusing system and optical zoom system for the portable devices, such as cell phones and cameras [33]. As to the pico-projection systems, attached a LC lens to a pico-projection system can help to electrically adjust the focusing properties of the projected image without mechanically adjusting position of a projection lens [43]. For the holographic projection system, a LC lens can help to correct the mismatch of chromatic image size which is important for the full-color holographic projection system [44]. For the ophthalmic lenses, the lens power of LC lenses can not only electrically tunable, but also can be positive or negative. LC lenses can be lenses to correct myopia. LC lenses can also be a kind of "extra-artificial crystalline lens" to compensate the degradation of the crystalline lens of eyes with age or the accommodations of eyes [45]. As to the endoscopic system, a LC lens can be adopted to electrically enlarge the depth-of-field of the endoscopic system [46]. LC lenses can also be used as a concentrator and a sun tracker in a concentrating photovoltaic (CPV) system [47–48]. The general concept is depicted in Fig. 5(a), 5(b) and 5(c). The system consists of a polarizer-free LC lens, a multi-junction solar cell, and a DC-AC

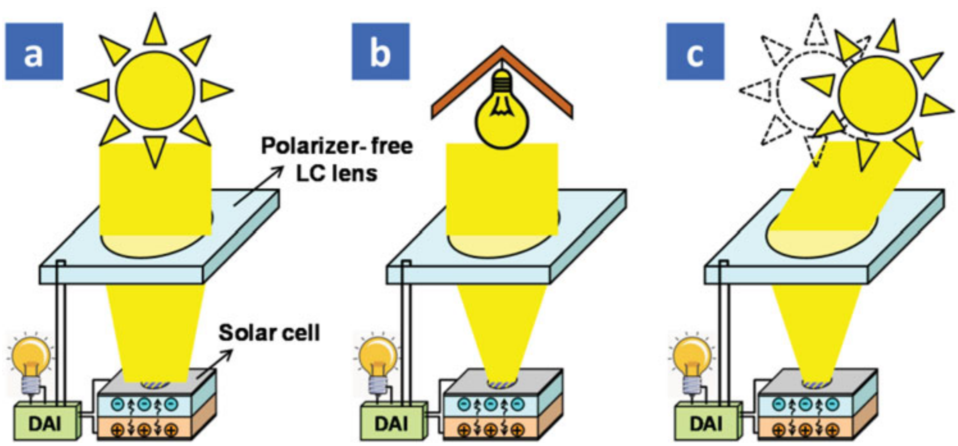

Figure 5. Operating principles of CPV system adopting a polarizer-free LC lens under (a) strong illumination, (b) weak illumination and (c) oblique incidence.

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inverter. When the sunlight passes through the LC lens, the LC lens modulates the photon-flux density and the direction of the sunlight. Under a strong illumination in Fig. 5(a), the LC lens is operating in a low concentration ratio to avoid the effect of the series resistance. Under a weak illumination in Fig. 5(b), the LC lens is operating in a high concentration ratio to increase the photocurrent. Furthermore, when the sun moves and the CPV system is under an oblique illumination, as shown in Fig. 5(c), we shift the focal point on the surface of the solar cell to guide the sunlight to the solar cell, and modulate the concentration ratio at the same time to preserve the incident photon-flux density. As a result, the output power of such a system is steady as the sunlight condition changes and the angle of incident light changes.

5. Conclusion

We review electrically tunable liquid crystal (LC) lenses and discuss three main challenges of LC lenses: the paradox between the response time and tunable focusing range, polarization dependency, and large aperture size for ophthalmic lenses. The solutions of those challenges are introduced. LC lenses have many applications, including auto-focusing imaging systems, auto-focusing projection systems, optical zoom systems, endoscopic systems, solar cells, ophthalmic lenses for myopia-presbyopia. Better solutions of three main challenges are still required and the performance of LC lenses still needs to be improved for practical industrial applications. No doubt, LC lenses bring great impacts in optical designs and optical systems.

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