Electrically tunable-focusing and polarizer-free liquid crystal lenses for ophthalmic applications

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Abstract: An electrically tunable-focusing and polarizer-free liquid crystal (LC) lens for ophthalmic applications is demonstrated. The optical mechanism of a LC lens used in human eye system is introduced. The polarizer-free LC lens for myopia-presbyopia based on artificial accommodation is demonstrated. The continuously tunable-focusing properties of the LC lenses are more practical in applications for different visional conditions of people. The concept we proposed can also be applied to another types of lenses as long as the focusing properties are tunable. The concept in this paper can also be extensively applied to imaging systems, and projection systems, such as cameras in cell phones, pico projectors, and endoscopes.

OCIS codes: (230.3720) Liquid-crystal devices; (230.2090) Electro-optical devices.

References and links

1. L. Werner, F. Trindade, F. Pereira, and L. Werner, "Physiology of accommodation and presbyopia," Arq. Bras. Oftalmol. **63**, 503–509 (2000).
2. E. Hermans, M. Dubbelman, R. van der Heijde, and R. Heethaar, "The shape of the human lens nucleus with accommodation," J. Vis. **7**(10), 1–10 (2007).
3. G.-Y. Yoon and D. R. Williams, "Visual performance after correcting the monochromatic and chromatic aberrations of the eye," J. Opt. Soc. Am. **19**(2), 266–275 (2002).
4. M. Jalie, *Opthalmic lenses & Dispensing*, 3rd. ed. (Elsevier/Butterworth Heinemann, 2008).
5. D. A. Atchison and G. Smith, *Optics of The Human Eyes* (Elsevier Science Limited, 2002).
6. H. Ren and S. T. Wu, *Introduction to adaptive lenses* (John Wiley & Sons, 2012).
7. E. J. Fernandez, L. Vabre, B. Hermann, A. Unterhuber, B. Povazay, and W. Drexler, "Adaptive optics with a magnetic deformable mirror: applications in the human eye," Opt. Express **14**(20), 8900–8917 (2006).
8. C. A. López and A. H. Hirsa, "Fast focusing using a pinned-contact oscillating liquid lens," Nat. Photonics **2**(10), 610–613 (2008).
9. H. C. Lin and Y. H. Lin, "A fast response and large electrically tunable-focusing imaging system based on switching of two modes of a liquid crystal lens," Appl. Phys. Lett. **97**(6), 063505 (2010).
10. H. C. Lin and Y. H. Lin, "An electrically tunable focusing pico-projector adopting a liquid crystal lens," Jpn. J. Appl. Phys. **49**(10), 102502 (2010).
11. M. Ye and S. Sato, "Optical properties of liquid crystal lens of any size," Jpn. J. Appl. Phys. **41**(Part 2, No. 5B), L571–L573 (2002).
12. S. Sato, "Liquid-crystal lens-cells with variable focal length," Jpn. J. Appl. Phys. **18**(9), 1679–1684 (1979).
13. H. C. Lin, M. S. Chen, and Y. H. Lin, "A review of electrically tunable focusing liquid crystal lenses," Trans. Electr. Electron. Mater. **12**(6), 234–240 (2011).
14. M. Ye and S. Sato, "Liquid Crystal Lens with Insulator Layers for Focusing Light Waves of Arbitrary Polarizations," Jpn. J. Appl. Phys. **42**(Part 1, No. 10), 6439–6440 (2003).
15. M. Ye, B. Wang, and S. Sato, "Polarization-independent liquid crystal lens with four liquid crystal layers," IEEE Photon. Technol. Lett. **3**, 505–507 (2006).
16. G. Q. Li, D. L. Mathine, P. Valley, P. Ayräs, J. N. Haddock, M. S. Giridhar, G. Williby, J. Schwiegerling, G. R. Meredith, B. Kippelen, S. Honkanen, and N. Peyghambarian, "Switchable electro-optic diffractive lens with high efficiency for ophthalmic applications," Proc. Natl. Acad. Sci. U.S.A. **103**(16), 6100–6104 (2006).
17. Y. H. Lin, H. Ren, Y. H. Wu, Y. Zhao, J. Fang, Z. Ge, and S. T. Wu, "Polarization-independent liquid crystal phase modulator using a thin polymer-separated double-layered structure," Opt. Express **13**(22), 8746–8752 (2005).
18. Y. H. Lin, H. S. Chen, H. C. Lin, Y. S. Tsou, H. K. Hsu, and W. Y. Li, "Polarizer-free and fast response microlens arrays using polymer-stabilized blue phase liquid crystals," Appl. Phys. Lett. **96**(11), 113505 (2010).
19. P. Valley, D. L. Mathine, M. R. Dodge, J. Schwiegerling, G. Peyman, and N. Peyghambarian, "Tunable-focus flat liquid-crystal diffractive lens," Opt. Lett. **35**(3), 336–338 (2010).

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20. 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).
21. A. F. Naumov, G. D. Love, M. Y. Loktev, and F. L. Vladimirov, “Control optimization of spherical modal liquid crystal lenses,” Opt. Express **4**(9), 344–352 (1999).
22. A. N. Simonov, G. Vdovin, and M. C. Rombach, “Cubic optical elements for an accommodative intraocular lens,” Opt. Express **14**(17), 7757–7775 (2006).
23. A. N. Simonov, G. Vdovin, and M. Loktev, “Liquid-crystal intraocular adaptive lens with wireless control,” Opt. Express **15**(12), 7468–7478 (2007).

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1. Introduction

For human eyes, the incident light passes through a cornea, a crystalline lens and retina of a human eye to form an image. Myopia and hypermetropia mainly result from anomaly of the length of eyes or anomaly of focusing power of cornea and the crystalline lens. However, presbyopia mainly originates from the age-related degradation of the crystalline lens and then affects the eye’s ability to focus, so-called amplitude of accommodation [1]. Declination of the amplitude of accommodation means that the difference between the farthest vision and the nearest vision decreases or becomes shorter. Such an amplitude of accommodation decreases linearly with the age and then turns out static (around 0 to 2D diopter, or m^{-1}) after age of 50 [2, 3]. The crystalline lenses of eyes are actually tunable-focusing lenses whose lens powers (i.e. an inverse of focal lengths) change with the curvatures of the lens surfaces [4, 5]. By adopting an extra-artificially tunable focusing lens or a lens with a tunable accommodation, the visional malfunction resulting from an aging crystalline lens can be corrected. Even though the natural accommodations of eyes disappear, elderly can still have their accommodations in vision with such an extra-artificial tunable focusing lens. Many literatures have been proposed on the electrically tunable focusing optical lenses, such as curvature-controlled liquid lenses, deformable mirrors, and liquid crystal (LC) lenses based on electrically controlled distribution of refractive indices [6–15]. The LC lenses on a basis of diffractive Fresnel lenses have been demonstrated in ophthalmic applications of presbyopia [16]. Such LC lenses require complex Fresnel electrodes and they have only two steps switches, on (focus) and off (no focus). As a result, delicate Fresnel patterns of such lenses need to be customized individually for different people. However, the general optical mechanism for designing the tunable ophthalmic lenses for presbyopia or myopia-presbyopia has not been reported. In this paper, we study the optical principles of designing the tunable ophthalmic lenses for myopia-presbyopia. Based on the concepts of artificially compensated lens power of the crystalline lenses of eyes, the tunable lenses possessing both adjustable positive and negative lens powers are suitable for myopia-presbyopia. We also experimentally demonstrated the concepts of ophthalmic lenses for myopia-presbyopia by a polarizer-free LC lens with aperture size of 6 mm. The concept of ophthalmic lenses we proposed is not only suitable for the LC lens, but also can be applied to other kinds of tunable focusing lenses. The concept in this paper can also be applied to imaging systems, and projection systems for portable devices.

2. Mechanism and operating principles

The image system of a human eye with an ophthalmic lens can be simplified as depicted in Fig. 1 (a). In Fig. 1(a), the system consists of a LC lens (ophthalmic lens), a cornea, a crystalline lens and a retina as an image sensor. The LC lens and the crystalline lens of the eye are tunable-focusing lenses. After light passes through the eye system, the image formations can be expressed as:

$$\frac{1}{d_o}+\frac{1}{d'}=P_{LC}(V), \tag{1}$$

$$\frac{1}{d_g-d'}+\frac{n}{d''}=P_C, \tag{2}$$

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$$\frac{n}{d_1 - d''} + \frac{n}{d_2} = P_{cryst} \cdot \tag{3}$$

where d_o is the distance between the solid lens and object, d_g is the distance between the LC lens and cornea, d_1 is the distance between the cornea and the lens in the eye, and d_2 is the distance between the retina and the lens in the eye. d' is the image distance of the first image after light passes through the LC lens and d" is the second image after light passes through the cornea. n is the refractive index of the eye ball (~1.333 in average), P_c is the lens power (or the inverse of the focal length) of the cornea (~42.735 m^{-1}) [5], P_{cryst} is the lens power of the crystalline lens in the eye, and $P_{LC}(V)$ is the voltage-dependent lens power of the LC lens. According to Eqs. (1)-(3), d_o can be solved as:

$$d_o = \frac{1}{P_{LC}(V) + S(P_{cryst})}, \tag{4}$$

where $S(P_{cryst})$ is the effective lens power of eyes which satisfies Eq. (5).

$$S(P_{cryst}) = \frac{-1}{d_g - \frac{1}{S'(P_{cryst})}}, \tag{5}$$

In Eq. (5), $S'(P_{cryst})$ satisfies Eq. (6).

$$S'(P_{cryst}) = P_c - \frac{1}{\frac{d_1}{n} - \frac{1}{P_{cryst} - \frac{n}{d_2}}} \cdot \tag{6}$$

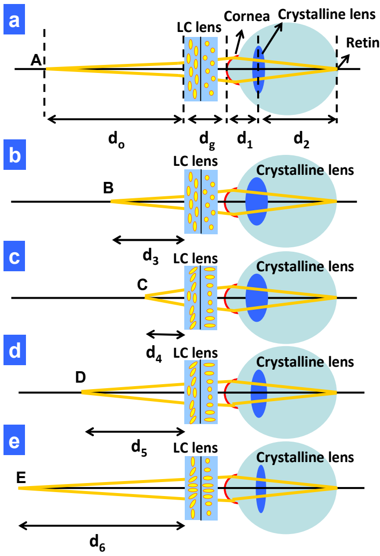

Fig. 1. Operating principles of an electrically tunable ophthalmic lens using a polarizer-free LC lens. (a)When the LC lens is off and the crystalline lens is relaxed (i.e. lens powers of both lenses are zero), the farthest point the eye can see is point A. (b) When the LC lens is still off, the eye can see near under the curvature change of the crystalline lens. The nearest point the eye can see is point B. (c) From (b), when the LC lens is turned on as a positive lens, the nearest point shifts to point C (i.e. $d_3 > d_4$). (d) From (c), the eye can clearly see the object in a range between point A and point C. (i.e. $d_0 > d_5 > d_4$) when we manipulate the lens powers of the positive LC lens and the crystalline lens. (e) When the LC lens is operated as a negative lens and the crystalline lens is relaxed, the farthest point eye can see is point E. ($d_6 > d_0$).

The operating principles of an electrically tunable ophthalmic lens on a human eye system are illustrated in Figs. 1(a)-1(e). Here is an example using a double-layered LC lens which is polarization independent or polarizer-free. When the LC lens is off and the crystalline lens is relaxed (i.e. $P_{LC}(V) = 0$ and $S\sim0$), the farthest point the eye can see is point A in Fig. 1(a). From Eq. (4), d_o is infinity. This means people with relaxed normal eyes (or emmetropia) can see clearly even though the object is at infinity. When the LC lens is still off, the eye can see closer under a curvature change of the crystalline lens (i.e. $P_{cryst} \neq 0$ and then $S\neq0$). The nearest point eye can see is point B in Fig. 1(b). From Figs. 1(a) and 1(b), when the crystalline lens changes the curvature, eyes can see objects clearly as the objects is located between point A and point B. This is so-called accommodation of eyes. We define the furthest and closest object points for the clear vision as the far point and the near point, respectively. In Figs. 1(a) and 1(b) the distance between the far and near points (i.e. point A and point B) is called the range of accommodation. The difference between $1/d_o$ and $1/d_3$ is defined as amplitude of accommodation.

For myopic people, d_o in Fig. 1(a) is no longer infinity, but a finite distance due to $S\neq0$. In Fig. 1(b), d_3 for the near point B depends on the maximum lens power of the crystalline lens. However, d_3 for the near point B increases with the age [4]. This means aging eyes cannot see clearly when the objects are too closed to the eyes. This is also called presbyopia. In order to compensate the degradation of accommodation originating from the aging crystalline lens, we can use a tunable focusing lens. In Fig. 1(c), when the crystalline lens has its maximum lens power and the LC lens is active as a positive lens (i.e. $P_{LC}(V)>0$) by means of adjusting the distribution of refractive indices of the LC lens under applied electric fields, the nearest point shifts from point B to point C (i.e. $d_3>d_4$). This also means the eye can clearly see the object in a range between point A and point C (i.e. $d_0>d_5>d_4$) by adjusting the lens powers of the positive LC lens and the crystalline lens in Fig. 1(d).

When the people suffer from presbyopia, the LC lens can assist people to see clearly as the object is nearby. Even though the crystalline lenses of eyes lose the function of accommodation, the LC lens can be an extra-artificial crystalline lens to help elderly to see objects close by. The lens power of the LC lens ($P_{LC}(V)$) can be expressed as [13]:

$$P_{LC}(V) = \frac{2 \cdot \delta n(V) \cdot d}{r^2}. \tag{7}$$

where d is the thickness of the LC layer (or cell gap), r is the radius of the aperture of the LC lens, and $\delta n(V)$ is the difference of the refractive indices between the rim and the middle of the aperture. When the people suffer from not only presbyopia but also myopia, the LC lens can help people in correcting both visional problems. By manipulating the distribution of LC molecules, the LC lens can be operated as a negative lens as well (i.e.$\delta n(V)<0$ and $P_{LC}(V)<0$). When the LC lens acts as a negative lens and the crystalline lens is relaxed (i.e. $S\sim0$), the far point is shifted from point A to point E, as shown in Fig. 1(e) (i.e. $d_6>d_0$). Therefore, by switching the lens power of the LC lens, we can realize an electrically tunable ophthalmic lens for presbyopia and even myopia-presbyopia owing to an artificial compensation of the accommodation of human eyes.

To demonstrate an ophthalmic lens using a LC lens, we have to design a polarizer-free LC lens with large aperture size. A LC lens usually requires a polarizer which decreases the light efficiency at least of 50%. To remove the requirement of a polarizer, a polarization independent LC phase modulation is required. Many polarization independent LC phase modulations are demonstrated and proposed [6, 17, 18]. Both of the large phase shift and the large aperture are required for ophthalmic lenses. As a result, the double-layered type LC phase modulation with large phase shift is more suitable. The optical mechanism of the polarization independency of the double-layered type LC phase modulation is based on the two eigen-polarizations of incident light experience the same phase shift contributed by two orthogonal orientations of LC layers [17]. In the double-layered type LC phase modulation, the phase shift is proportional to the birefringence of LC and the thickness of the LC layer.

The double-layered type LC phase modulation shows lensing effect after we apply an inhomogeneous electric field. For a good image quality, the phase profile of the LC lens is parabolic. Assume that the applied voltage (V) at the rim of the lens aperture is larger than the threshold voltage and V = 0 at the center of the lens aperture. The phase difference (Γ) between the rim and the center of the LC lens can be expressed as [17]:

$$\Gamma = \frac{2\pi}{\lambda} \cdot (\Delta n \cdot d), \tag{8}$$

where Δn is the birefringence of LC materials. The focal length (f) of the LC lens based on the double-layered type LC phase modulation can be expressed as [17]:

$$f = \frac{\pi \cdot r^2}{\Gamma \cdot \lambda}. \tag{9}$$

The inverse of Eq. (9) equals to Eq. (7). By adding lots separated multi-layers in a cell, the double-layered type of LC phase modulations can enlarge the phase shift. Even though the birefringence of LC is limited (<0.5), the polarizer-free LC lenses still can be developed to realize ophthalmic lenses. In our previous work for discussing the double-layered type LC phase modulation, the middle cell separator requires two identical anisotropic polymeric layers [17]. Here, we redesign the structure of the LC lens by adopting a polymeric layer which is optically isotropic due to the long axes of LC directors of the polymeric layer perpendicular to the glass substrates as shown in Fig. 2(a).

3. Experimental results and discussions

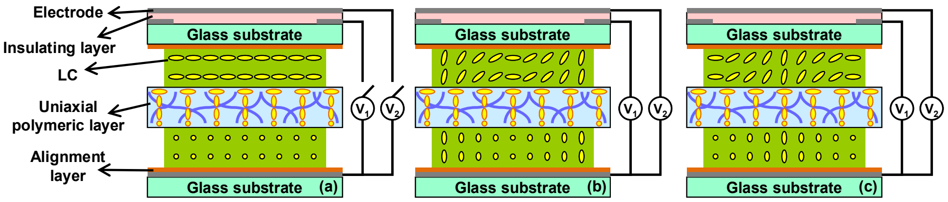

Fig. 2. The structure of the polarization independent LC lens at (a) $V_1 = V_2 = 0$, (b) $V_1 > V_2$, (c) $V_1 < V_2$. The focal length is infinity in (a), positive in (b), and negative in (c).

The structure of such a LC lens consists of Indium Tin Oxide (ITO) electrodes, an insulating layer of polymer NOA81(Norland), two glass substrates, alignment layers of polyvinyl alcohol (PVA), two LC layers and a separator of a polymeric layer to separate two LC layers. The function of the middle polymeric layer cannot only align LC directors, but also be a cell separator; meanwhile, the optical properties of the polymeric layer are also polarization independent. Compared to the conventional one using a glass substrate as a separator, the polymeric layer possesses the advantages of a thin thickness, no need of an extra-alignment layer, and easily to be embedded into the double-layered structure. The fabrication process of the polymeric layer is as follows. We filled nematic LC (Merck, MLC 2070, Δn = 0.26 for λ = 589.3 nm at 20°C), reactive mesogen (Merck, RM 257), and photoinitiator (Merck, IRG-184) at 20:79:1 wt% ratios into the gap between two ITO glass substrates coated with PVA layers whose rubbing directions were orthogonal to each other. The thickness between those two ITO glass substrates was 50 μm and then we applied voltages of 300 V_{rms} (frequency was 1kHz) on ITO electrodes in order to reorient LC directors along electric fields. Then the cell was exposed to UV light (~3mW/cm^2) for 1 hour for photo-polymerization. After photopolymerization, we peeled off the glass substrates by a thermal releasing process and obtained the polymeric layer. After peeling, the polymeric layer was assembled with two coated glass substrates (thickness = 2.1mm), and nematic LC mixture of MLC-2070 to construct the structure of the LC lens depicted in Fig. 2(a). The thickness of each LC layer in Fig. 2(a) was 50 μm controlled by mylar films. The aperture size of the LC lens was 6 mm. In

Fig. 2(a), the rubbing directions of two alignment layers were perpendicular to each other. Actually, we can also use homeotropic alignment of the polymeric layer before polymerization, but the LC materials in the LC layers should be chosen properly.

Without applied voltages, the lens power of the LC lens is zero (Fig. 2(a)). When the applied voltage $V_2 > V_1$, the LC lens is a negative lens because the LC directors around the rim of the aperture are parallel to the glass substrates and the LC directors inside the aperture are more perpendicular to the glass substrates as shown in Fig. 2(c). Thus, an incident plane wave is converted to a diverging parabolic wave by the negative LC lens. Similarly, the LC lens is a positive lens when the applied voltage $V_2 < V_1$, as shown in Fig. 2(b). An incident plane wave is then converted to a converging parabolic wave by the positive LC lens. By changing the magnitude of the voltages, the focal length of the LC lens is electrically switchable.

To measure the tunable focusing properties of the LC lens, the LC lens was attached on a camera (Canon 500D, SIGMA 17-70mm MACRO HSM). The camera consists of a lens module with the equivalent focal length of 27 mm to 112 mm depending on the distance between the lenses of the lens module and an image sensor with 15.1 mega pixels. To measure the positive lens power (i.e. the positive value of the inverse of focal length within the unit of m^{-1}) of the LC lens, a resolution chart with a spatial frequency of 1.213 lp/mm was placed 50 cm in front of the camera and we adjusted the lens module to see the clearest image of the resolution chart. We then attached the LC lens right in front of the camera. When the applied voltage of V_2 (f = 1kHz) within maintaining V_1 of $160V_{rms}$ (f = 1kHz) was changed, we adjusted the location of the resolution chart until the image of the resolution chart was clear again. We then recorded the voltages and the distance between the resolution chart and the LC lens. Such a distance is the focal length of the LC lens as a positive lens. To measure the negative lens power of the LC lens, we placed the same resolution chart at 50 cm away from the camera and adjusted the camera module until we saw the clearest image. Then we attached the LC lens on the camera. Every time we changed the applied voltage of V_1 (f = 1kHz) within maintaining V_2 of $160V_{rms}$ (f = 1kHz), we adjusted the location of the resolution chart until the image of the resolution chart was clear. We then recorded the voltages and the distance between the resolution chart and the LC lens. Such a distance can be converted to the lens power. For example, when the distance is 100 cm, the lens power is −1D by calculating from the equation of the image formation: $1/1-1/0.5 = -1$ D (Diopter or m^{-1}). The measured lens power of the LC lens as a function voltage V_1 or V_2 is depicted in Fig. 3. The lens power of the LC lens is capable of switching from −1.2D (Diopter or m^{-1}) to + 2D. The measured response time is around 2 sec for switching + 2D to −1.2 D. (The data are not shown here.) Since the LC lens is polarization independent, all the measurements related to the LC lens do not adopt any polarizer.

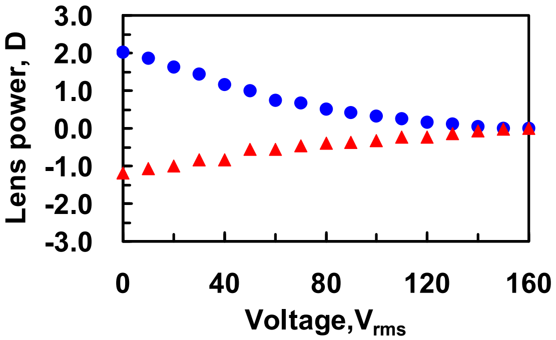

Fig. 3. The lens power of the LC lens as a function of applied voltage. Blue dots represent the positive lens power with changing V_2 at $V_1 = 160\ V_{rms}$. Red triangles represents the negative lens power with changing V_1 at V_2 = 160 Vrms. f = 1kHz.

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To demonstrate the concept of an electrically tunable ophthalmic lens for myopia-presbyopia and to measure the performance, we exploited the same camera to mimic a presbyopic eye with amplitude of accommodation of 2D, a common presbyopic vision for people at the age of 50, by means of adjusting the equivalent focal length of lens module of the camera. The LC lens was directly attached on the camera. Then we performed the similar measurement to record the objective distance. Figures 4(a) and 4(b) show the objective distance as a function of accommodation of the camera at different lens power of the LC lens. Without the LC lens (i.e. 0D), eyes can see the objective clearly from 100 cm to 31.6 cm. (Black squares in Figs. 5(a) and 5(b))When the LC lens is switched to a negative lens with a lens power of −1D with applied voltages (V_1, V_2) = (20 V_{rms},160 V_{rms}), eyes can see clearly from ~360 cm to ~49.3 cm. (Pink triangles in Figs. 4(a) and 4(b)) This means the eyes can see farther and it also indicates the correction of myopia. When the LC lens is switched to a positive lens with a lens power of + 1D with applied voltages (V_1, V_2) = (160 V_{rms}, 50 V_{rms}), eyes can see clearly from ~49.3 cm to ~23.5 cm. (Blue dots in Figs. 4(a) and 4(b)) This means people can see closer with adding + 1D lens power of LC lens. When the LC lens is switched to a positive lens with a lens power of + 2D with applied voltages (V_1, V_2) = (160 V_{rms}, 0 V_{rms}), eyes can see clearly from ~32.5 cm to ~19 cm. (Red diamonds in Figs. 4(a) and 4(b)) In Figs. 4(a) and 4(b), people can see nearer with an assistance of a positive lens power of the LC lens and people can see farther with an assistance of a negative lens power of the LC lens. This also means the LC lens can correct myopia and presbyopia together by changing the applied voltages of the LC lens. When people lost the ability of accommodation (i.e. 0D of accommodation of camera in Figs. 4(a) and 4(b)), they can still see the objective clear in a range from 360 to 32.5 cm with extra artificial accommodation of the LC lens whose lens power is electrically switchable. In our measurement, the errors mainly result from the depth-of-field of the image, especially large depth-of-field as the object is larger than 100 cm.

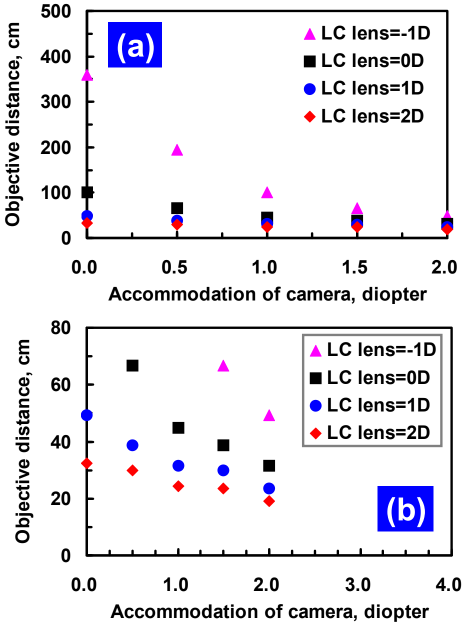

Fig. 4. (a)The objective distance as a function of accommodation of camera at different lens power of the LC lens. The camera was set to mimic a myopic-presbyopic eye with amplitude of accommodation of 2 D. (b) The same Fig. 4(a) with different range of the objective distance.

Figures 5(a)-5(d) show the image performances of the LC lens for myopia-presbyopia. The LC lens was still attached on the camera and took photos directly under an ambient white light. Four pieces of objective papers with symbols were placed at 360 cm, 100 cm, 33 cm and

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20 cm away from the LC lens. We adjust the camera properly in order to mimic the human eyes with myopia-presbyopia. At first, the camera did not have any accommodation (i.e. 0D). When the lens power of the LC lens was 0D, the objective at 100 cm could be seen clearly. (Fig. 5(b)) That means the far point was 100 cm. When the lens power of the LC lens was −1D, the objective at 360 cm was clear.(Fig. 5(a)) The vision is corrected by the LC lens with a negative lens power. When the lens power of the LC lens was switched to 2D by adjusting applied voltages, the objective at 33 cm was clear. (Fig. 5(c)) The objective at 20 cm was also clear as both of the accommodation of camera and the lens power of the LC lens were 2D. (Fig. 5(d)) This means that under assistance of the accommodation of crystalline lenses of eyes and the lens power of the LC lens, people can see the object closer. As a result, people with myopia-presbyopia can see farther and see nearer when the LC lens was operated as a positive or a negative lens even though people possess only limit accommodation of the crystalline lens of eyes.

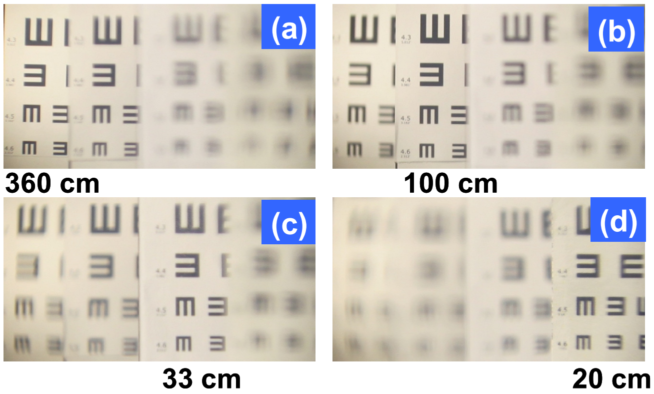

Fig. 5. Image performances of the eyeglasses for myopia-presbyopia. Four pieces of objective papers with symbols are placed at 360 cm, 100 cm, 33 cm and 20 cm. (a) When the lens power of the LC lens is −1D, the objective at 360 cm is clear. (b) When the lens power of the LC lens is 0D, the objective at 100 cm is clear. (c) When the lens power of the LC lens is 2D, the objective at 33 cm is clear. The accommodation of camera = 0D in (a), (b), and (c). (d) The objective at 20 cm is also clear under both of the accommodation of camera = 2D and the lens power of the LC lens = 2D.

The LC lens as a positive lens can help to decide a new near point in vision in order to correct presbyopia, and the LC lens as a negative lens can help to decide a new far point in vision in order to correct myopia. Moreover, the LC lens can be operated as a positive and a negative lens at the same time to correct myopia-presbyopia. It looks that the LC lens only need to switch between on and off (focus and out of focus), instead of continuously tunable focusing properties of eyeglasses. However, the LC lens still needs continuously tunable focusing properties for practical applications. The reason is as follows. The eye conditions or visions are different for different people. The LC lens with continuously tunable focusing properties is suitable for different visions just by setting different applied voltage. Even though a person has the degradation of the vision with time, the person can electrically adjust the LC lens by himself. This is more practical for application. In comparison, the conventional diffractive type of tunable eyeglasses only has on and off states [16]. When people experience the degradation of presbyopia with age, they have to re-design the complicated and expensive diffractive pattern of the tunable eyeglasses. In spite of the improvement of 4-steps design of the diffractive type of eyeglasses, the tradeoff is the decrease of diffraction efficiency from ~98% to ~40% [19]. Our design of LC lens has several advantages: a compact in-cell structure, reduction of the interfacial reflection, and no need extra alignment layer for the polymeric layer compared with the LC lens with 4 LC layers [15]. To further enlarge the tunable range of the lens power and the aperture size of the LC lens, some methods should be

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adopted according to Eq. (6), such as large cell gap, high birefringence of LC materials or other LC modes [20–23]. The polarization independent LC lens we proposed in this paper provides good image performance and easy fabrication process compared to the diffractive-type LC lenses [16].

4. Conclusion

We demonstrated a tunable ophthalmic lens by using a polarizer-free LC lens. The myopia and presbyopia could be corrected. We also studied the optical principles of designing the tunable eyeglasses and also experimentally demonstrated the concepts. The concept we proposed can also be applied to another types of tunable focusing lenses, such as liquid lenses. The tunable range of the lens power of the LC lens can be improved by adding LC layers, increasing the thickness of the LC layer, and adopting LC materials with high birefringence [13]. To lower the driving voltage of the LC lens, we can coat a thin layer with high impedance on the electrodes or increase the relative permittivity (or dielectric constant) of the glass substrates [13]. Adding other polymeric layer with a distribution of the relative permittivity can also reduce the applied voltage ($< 5V_{rms}$) [20]. Moreover, multiple layers of the LC lens can be adopted to increase the phase of the LC lens in order to enlarge the aperture size with a large tunable range. Therefore, the LC lenses are able to provide a full corrected field of vision and are not dimensionally limited. In terms of future clinical ophthalmic use, the aspherical phase profile of the LC lenses, special aberrations for some diseases (e.g. astigmatism), chromatic properties, and optical properties for oblique light should also be considered in the designs of the LC lenses. We believe this study provides a guideline to help the researchers and engineers to develop the electrically tunable ophthalmic lenses. The concept in this paper can also be applied to cameras in cell phones, pico projectors, and endoscopes.

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