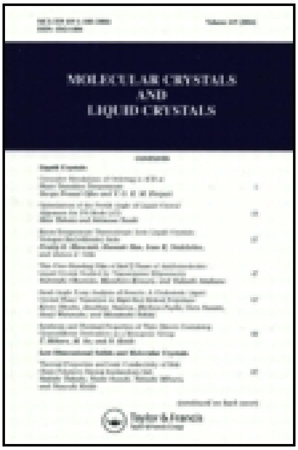

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Electro-Optic Adaptive Lens as a New Eyewear

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Adaptive lens with the capability of changing the focusing power has important applications in 3D imaging, optical information processing, and ophthalmology. We demonstrate a switchable electroactive lens with very high diffraction efficiencies using a circular array of electrode pattern filled with liquid crystal as the active medium to be used as an adaptive eyewear. Electrically adjustable lens allows the focal length to be voltage controlled without bulky and inefficient mechanical movement. Binary Fresnel zone plates using liquid crystal as active material have been demonstrated for imaging applications, but the diffraction efficiency is low. The lens is flat and the thickness of the liquid crystal is 5 μm. Diffraction efficiencies exceeding 90% has been achieved for an 8-level diffractive lens. The lens can be operated as both positive and negative lens. Design,

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modeling, fabrication, and characterization of the lens is presented. Using nematic liquid crystal, the lens is polarization dependent and two crossed lenses are integrated to form a complete lens. The ON- and OFF-state of the electrically controlled lens allow near- and distance-vision respectively for presbyopia eyes.

Keywords: ■

1. INTRODUCTION

Spectacle correction of age-related optical changes in the eye has been increasingly important. With aging, the eye loses some of its elasticity and becomes less able to focusing incoming light. The result is that the eye has difficulty in switching easily between focusing on a near object and a distant object. Some presbyopes wear reading glasses such as bifocal, trifocal, or progressive with some complaining about putting on and taking off of their glasses repeatedly and others complaining about the dizziness brought about by wearing progressive lenses. Such eyewear enable the eye to focus on both near and distant objects at the same time by use of area division. The user is confronted with two images and the vision quality is compromised. Except the bifocal diffractive lens [1], the field of view for each vision is limited to a narrow corridor. Furthermore, they do not work well when the pupil is small, since the iris blocks the beam that passes through the annular portion of the lens. Another choice is to use monovision lenses by which different focusing power is provided to each eye, one for near and the other for distant objects. However, in this case the binocular depth perception is affected. Ophthalmic lenses are more attractive if they allow the freedom of adaptively changing the focusing power [2,3]. Electrically controllable focusing lens can achieve this goal with the greatest field of view and high image quality without switching between the lenses. The electroactive lens allows the focal length to be voltage controlled without bulky and inefficient mechanical movement. Different structures for liquid crystal adaptive lens have been suggested for various applications, e.g., by immersing microlens in liquid crystal [4,5] or by sandwiching liquid crystal in planar electrode plates [6–12] with gradient refractive index change. The latter makes the liquid crystal alignment easier and the cell thinner which permits faster switching. The Fresnel zone structure allows relatively large aperture, which is required for ophthalmic lenses. A few binary Fresnel zone plates [13–17] using liquid crystal as active material have been demonstrated for imaging applications, but little practical success has been made for adaptive ophthalmic lens [18] since the diffraction efficiency is low.

In this paper we show that a high-efficiency switchable electro-optic diffractive lens can be produced as an adaptive eyewear. The lens is flat with the liquid crystal thickness of 5 μm. Diffraction efficiencies of exceeding 90% have been achieved for 1-diopter and 2-diopter lens. The ON- and OFF-state of the electrically controlled lens allow near- and distance-vision respectively for presbyopia eyes. Other advantages of this lens include compact, lighter weight, potential low cost and easier operation with low voltages and low power dissipation.

2. STRUCTURE OF THE ELECTRO-OPTIC DIFFRACTIVE LENS

The function of the diffractive lens is based on diffraction by a Fresnel zone pattern [19]. The basic structure of a diffractive lens is illustrated in Figure 1. Figure 1(a) shows a part of a refractive lens. By removing

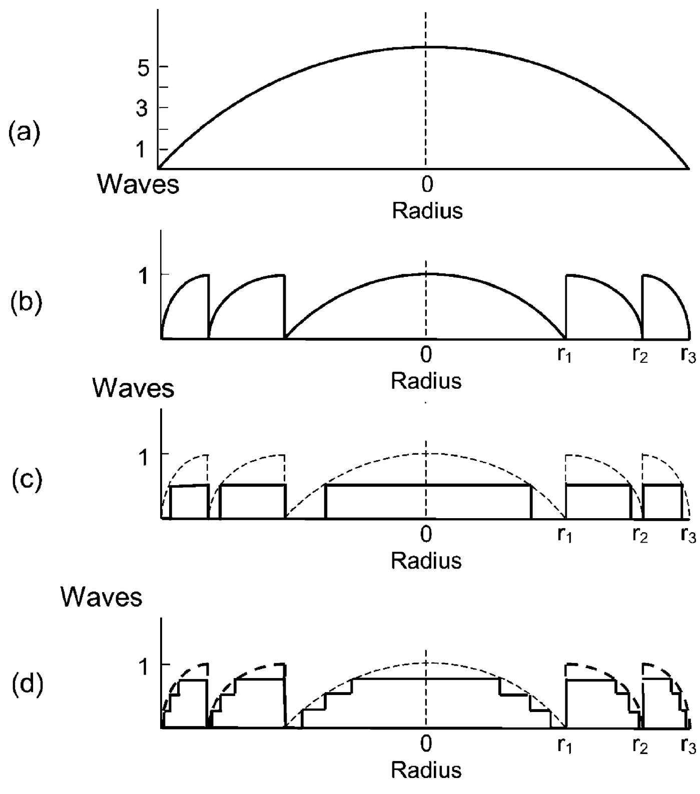


FIGURE 1 Illustration of a diffractive lens: (a) conventional refractive lens; (b) (diffractive lens with continuous quadratic blaze profile; (c) binary diffractive lens; (d) four-level approximation of the diffractive lens.

the multiple 2π phase retardation from the refractive lens, we obtain a diffractive lens as shown in Figure 1(b). The phase jump at each zone boundary is 2π for the design wavelength λ_0, and the blazing profile in each zone makes perfect constructive interference at the focal point. Figures 1(c) and 1(d) show different approximations of the desired phase profile in Figure 1(b). In each zone, multiple steps are used to approximate the desired phase profile. The structure is periodic in r^2 (r is the radius), and the period equals to r_1^2, where r_1 is the radius of the first zone. Each zone (subzone) has the same area as r_1^2 (r_1^2/N). The focal length of the diffractive lens is

$$f = \frac{r_1^2}{2\lambda}, \tag{1}$$

which implies that the focal length can be changed by choosing the zone period. For a lens with the focal length $k \cdot f$ (k is an integer), the size (area) of each zone is $k \cdot r_1^2$. The diffraction efficiency of a multi-level diffractive lens is given by

$$\eta = \sin c^2\left(\frac{1}{N}\right). \tag{2}$$

Here we consider the nematic liquid crystal lens (Fig. 2(a)), where the phase profile is obtained by electrically controlled birefringence effect. A nematic liquid crystal layer is sandwiched between a patterned electrode substrate and a ground electrode substrate. The patterned electrode is fabricated by photolithographic processing of an indium-tin-oxide (ITO) film deposited on a glass substrate, and the ground electrode substrate contains a uniform conductive ITO layer. The patterned electrodes consist of a circular array of rings. Both of the two electrode surfaces are coated with polyvinyalcohol (PVA) as an alignment layer and are treated by rubbing to give a homogeneous molecular orientation. The refractive index of the extraordinary beam is changed due to the reorientation of the liquid crystal molecule when a voltage is applied to the medium. The phase profile across the lens is tailored by applying proper voltages to the patterned electrodes and it determines the diffraction efficiency, the most important performance parameter of a diffractive lens. The phase profile may be affected by various factors, including the quantization error (number of phase levels in each zone), the gaps between the electrodes, fringing field effect in the transition area of neighboring zones, and fabrication errors. Increasing the number of phase levels in each zone can reduce the quantization error. For instance, an ideal diffractive lens with 8-, 4-, and 2-level digitization corresponds to efficiency of 95.0%, 81.1%,

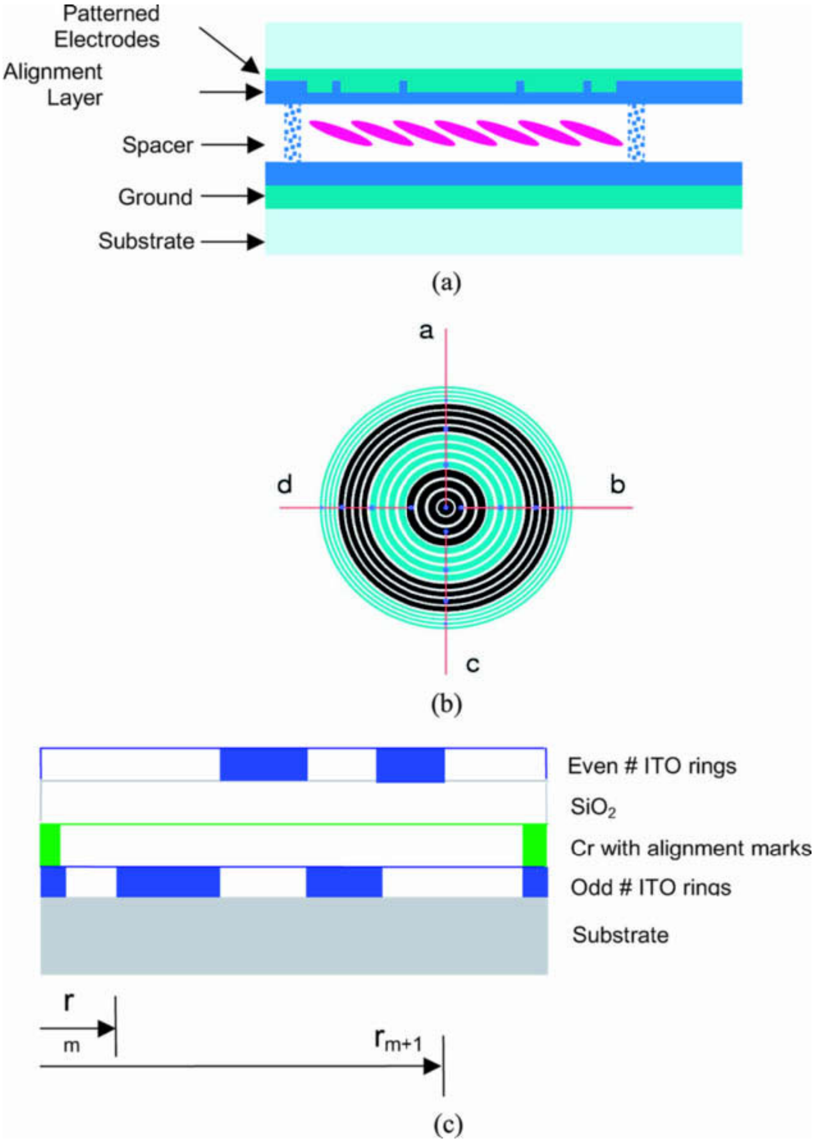


FIGURE 2 Adaptive liquid crystal diffractive lens. (a) Structure of the liquid crystal lens. (b) Layout of the one-layer electrode pattern. Adjacent zones are distinguished by blue and black colors. An electrical insulation layer is added with vias (represented by blue dots), enabling greater interconnection complexity. Each bus connects one electrode in each zone. (c) Structure of the two-layer electrode pattern.

and 40.5%, respectively. Simulation shows that the gaps between the electrodes and different types of phase distortion at the electrode boundaries greatly affect diffraction efficiency and other performance. To alleviate this effect, the odd- and even-numbered rings can be interleaved into two layers that are separated by an insulating layer such as SiO_2. In our experiments, all the nth ($n = 1, 2, \ldots, L$) subzones of the M Fresnel zones are connected together by a bus line, i.e., applied the same voltage, and thus have the same phase value. Figure 2(b) illustrates the layout of the one-layer electrode pattern. Figure 2(c) shows the cross section of the two-layer electrode pattern, where odd- and even-numbered rings are distributed in two layers and there are no gaps between two neighboring electrodes. In this case, for phase steps larger than 4, the electrodes can be addressed from an additional layer through vias as in the one-layer case.

3. CHARACTERIZATION OF THE LENS

When the device is fabricated, various optical characterizations are performed. Imaging ellipsometry is used to check the electro-optic function of each electrode. Transmission of the lens over the visible spectrum is above 85% if there is no antireflection coating on the surfaces. Diffraction efficiency is measured as a function of beam

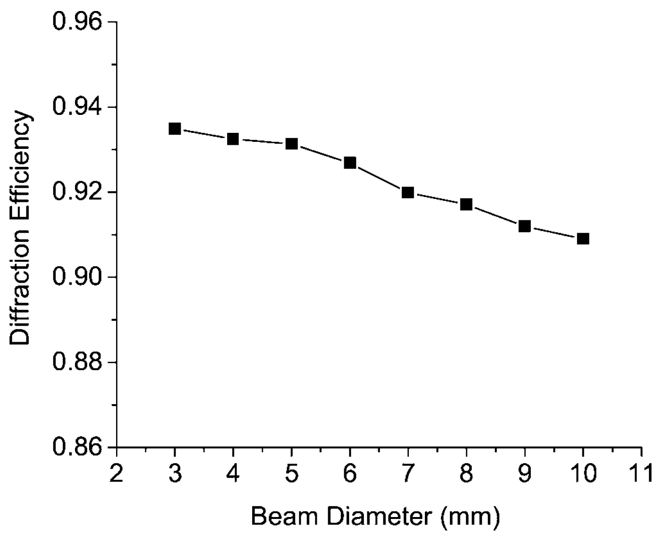


FIGURE 3 Diffraction efficiency as a function of the beam diameter for a 1-diopter lens.

diameter is shown in Figure 3. To do this, the diffraction efficiency is measured as a function of the active area by using an iris that is placed at the center of the lens, thus showing the diffraction efficiency for various beam sizes. The decrease of efficiency for larger beam sizes is the result of phase distortion caused by the fringing field that has more significant effect on the outer zones. The efficiency of the center area is close to the theoretical value as the fringing field effect is negligible in this area. The diffraction efficiency as a function of the position of the lens was also measured by using a small probe beam (about 2 mm in diameter) that is moved from the center to the edge of the lens with an increment of 1 mm.

A Mach-Zendar interferometer is used to measure the wavefront immediate behind the lens, the focal length, and modulation transfer function (MTF). They show excellent imaging capability of the lens. Strong modulation of the optical power is observed in interferogram of the lens in the optically active state. The focusing power was estimated to be 1.002 diopter, in excellent agreement with the design value. Very good spherical profiles were obtained in both x and y cross sections, indicating small aberrations. Higher-order aberrations were estimated by analyzing the difference between the measured

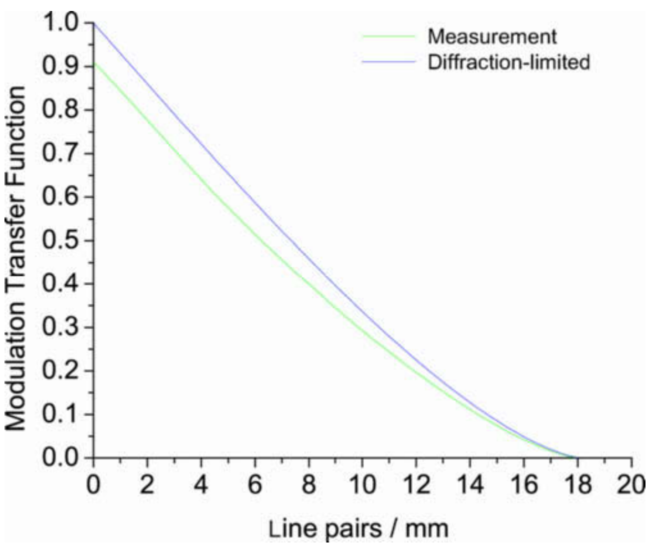


FIGURE 4 Modulation transfer function of the lens. The green line is obtained from the measurement data, while the blue line is for a diffraction-limited lens. The value at low spatial frequency is determined by the diffraction efficiency of the lens.

wavefront and a best-fit spherical wave and tilt. The modulation transfer function (MTF) indicated near diffraction-limited performance as shown in Figure 4. All these properties make the switchable lens suitable for ophthalmic applications.

The focal length is 50.855 cm at 543.5 nm. With Eq. (2), the focal length at 555 nm can be calculated as 49.80 cm, which corresponds to a focusing power of 2.008 diopter and indicates that accurate focusing power can be achieved with this technique. The higher order aberrations were estimated by the unwrapped phase minus the phase of tilt and focusing. The RMS value is 0.0918λ. Figure 4 shows the

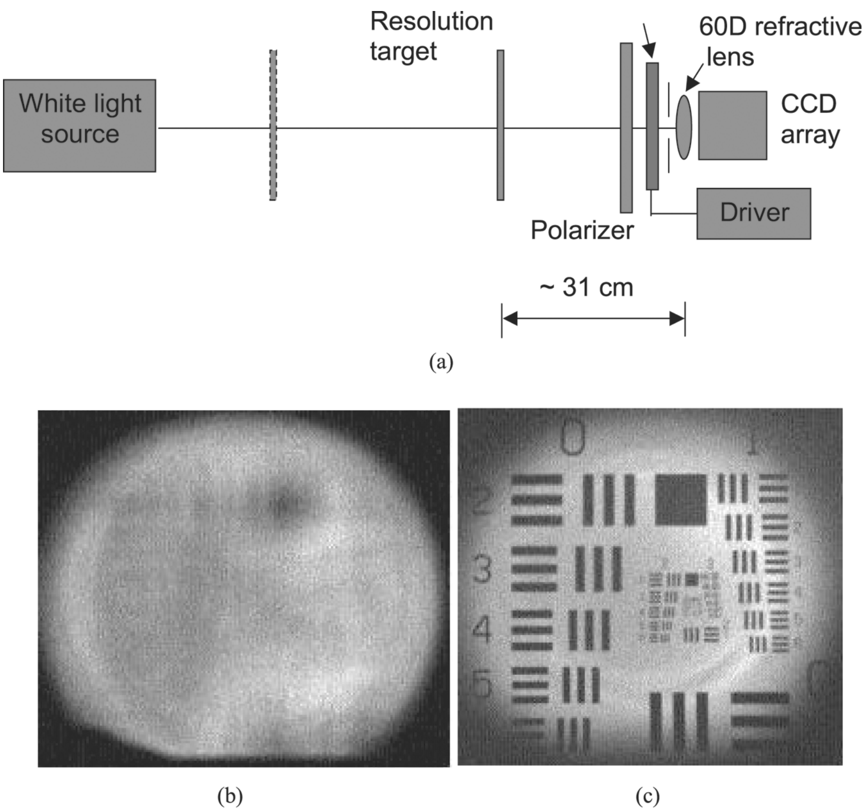
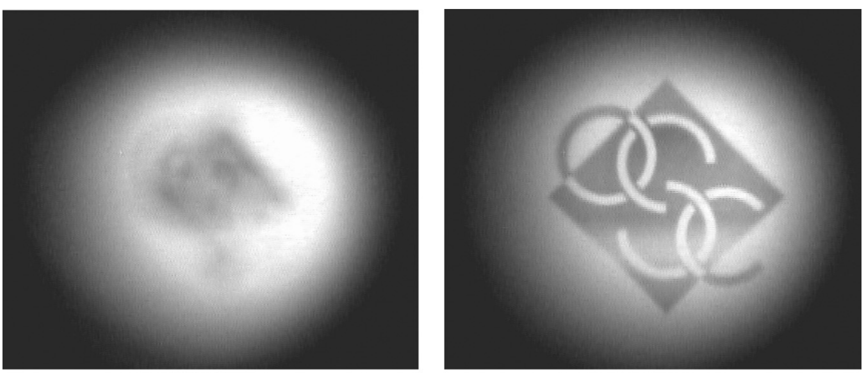


FIGURE 5 Hybrid imaging using the electro-active diffractive lens with the model eye. The function of the diffractive lens is to provide near vision correction to the model eye. (a) Schematic diagram. (b) The object is placed at a reading distance ($\sim$31 cm). The image is severely out of focus in the model eye when the diffractive lens is OFF. (c) When the diffractive lens is activated, the object is imaged clearly.

modulation transfer function, which is close to the diffraction-limited curve. The focused spot size was measured using a beam profiler and is also close to the diffraction-limited spot.

The lens has been demonstrated to provide near vision correction for the model eye. Figure 5(a) shows the schematic diagram for hybrid imaging using the electro-active diffractive lens with the model eye. The model eye consists of a 60 D refractive lens, iris, photopic filter and CCD array. A white light source illuminates the object (an Air Force resolution target), which is placed at a reading distance ($\sim$30 cm). There is no accommodation in this model eye. When the diffractive lens is not activated, the image is blurred in the model eye (Fig. 5 (b)). When the diffractive lens is turned on, the target is moved back and forth to obtain the best focus, and when the target is about 31.5 cm away from the model eye, the object is imaged clearly. For a prysbyopia eye, when the diffractive lens is ON, the subject can see objects in the reading distance, and when the diffractive lens is OFF, the subject can see the objects in greater distance.

Using nematic liquid crystal, the electro-optic effect takes place for one polarization state of the incident light, which is the extraordinary beam of the material. Because of this polarization sensitivity, two liquid crystal lenses with orthogonal initial preferential directions are required to form a complete lens that can focus any randomly polarized plane wave to a point. Since the polarization component



(a) (b)

FIGURE 6 Hybrid imaging using the complete electro-active diffractive lens with the model eye. No polarizer is needed in front of the diffractive lens. (a) The image is severely out of focus in the model eye when the diffractive lens is OFF; (b) When the diffractive lens is activated, the object is imaged clearly.

focused by the first cell also passes through the second cell, in order to allow the light polarized in the two directions focused to the common plane and reduce aberration in imaging, the complete lens should be as thin as possible. This also makes the device more compact. Figure 6 shows the imaging results of a complete lens using the setup in Figure 5(a) but without the polarizer. When both single lenses are turned on, the object is clearly imaged onto the CCD camera (Fig. 6 (a)). In contrast, when both lenses are turned off, the image is severely blurred (Fig. 6 (b)).

4. CONCLUSION

We have demonstrated a high-efficiency switchable electro-optic adaptive diffractive lens for vision correction of presbyopia eyes. Diffraction efficiencies exceeding 90% have been achieved for an 8-level lens. The focusing power of the lens can be adjusted to be either positive or negative, depending on the voltages applied to the patterned electrodes.

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