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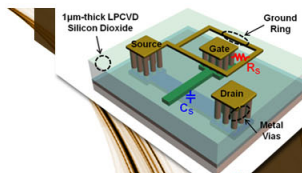
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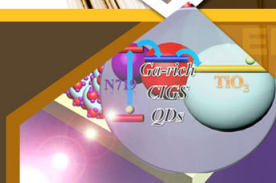
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Large-aperture switchable thin diffractive lens with interleaved electrode patterns

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The authors report on a high-performance large-aperture switchable diffractive lens using nematic liquid crystal that can be used as an adaptive eyewear. The odd- and even-numbered ring electrodes are separated in two layers, avoiding the gaps between the neighboring electrodes and allowing high diffraction efficiency. It is easier to avoid shorts between neighboring conductive electrodes and fabricate lenses with larger aperture and smaller feature size. With a four-level phase modulation, a 15 mm aperture, 2 dpt lens with small aberrations and diffraction efficiency of above 75% could be demonstrated with low operating voltages. The thickness of the liquid crystal is only 5 μm . The lens switching time is about 180 ms. The on and off states of the electrically controlled lens allows near and distance vision, respectively. The focusing power of the lens can be adjusted to be either positive or negative. This structure can be extended to higher-level phase modulation with even higher efficiencies. © 2006 American Institute of Physics. [DOI: 10.1063/1.2338646]

Spectacle correction of age-related optical changes in the eye has been increasingly important. With aging, the eye's lens loses some of its elasticity and becomes less able to focus incoming light. The result is that the eye has difficulty in switching easily between focusing on a near object and a distant object, a condition called presbyopia. To correct for this condition, various eyeglasses, including bifocal, trifocal, or progressive, or contact lenses have been developed to enable the eye to focus on both near and distant objects by looking through a different section of the lens, an approach referred to as area division. With the exception of the bifocal diffractive lens,¹ the field of view for each type of vision is generally limited to a narrow corridor. 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 will be more capable and attractive if one could change their focusing power.²⁻⁴ Although fluidic adaptive lenses have been demonstrated,⁵ an electrically controllable focusing lens is more suitable for this application. An electroactive lens allows for a greater field of view with the entire aperture and the focal length to be voltage controlled without mechanical motion. Different structures for liquid crystal (LC) adaptive lenses have been suggested for various applications, e.g., by filling empty lens shaped cavities with LC (Refs. 6 and 7) or by sandwiching LC between planar electrode plates⁸⁻²¹ and generating a refractive index gradient. The latter permits a power-failure-safe configuration for driving and thinner LC layers with fast switching, both of which are critical for ophthalmic lenses. However, the apertures of those lenses are not large enough, or high working voltages are required, or the LC layer is still relatively thick. The Fresnel zone structure allows relatively large aperture. A few binary Fresnel zone plates²²⁻²⁴ using LC as the active material have been demonstrated for imaging applications, but they did not provide viable solutions for

adaptive ophthalmic lenses.²⁵ Therefore, it is important to investigate the approach that allows large aperture, fast response time, low operating voltages, high diffraction efficiency, and power-failure-safe configuration. In this letter, we present a design for high-efficiency switchable diffractive lens by separating odd- and even-numbered ring electrodes into two layers and thus eliminating the gaps between the neighboring electrodes. Compared to the design with the one-layer electrode pattern, another advantage of this concept is that it is easier to overcome shorts between neighboring conductive electrodes and fabricate lenses with larger aperture and smaller feature size.

The function of the diffractive lens is based on diffraction by a Fresnel zone pattern.²⁶ By removing the multiple 2π phase retardation from the refractive lens, a diffractive lens is obtained as shown in Fig. 1(a). The phase jump at each zone boundary is 2π for the design wavelength λ_0 , and the blazing profile in each zone provides for perfect constructive interference at the focal point. Figure 1(a) shows a four-level approximation (solid line) of the desired phase profile (dashed line). 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 , N is the discrete phase levels). The focal length of the diffractive lens is $f=r_1^2/2\lambda$. The diffraction efficiency of a multilevel diffractive lens is given by $\eta=\text{sinc}^2(1/N)$. Here we consider the nematic LC lens [Fig. 1(b)], where the phase profile is obtained by the electrically controlled birefringence effect. A nematic LC layer (E7 from Merck with birefringence greater than 0.2) is sandwiched between a patterned electrode substrate and a ground electrode substrate. The patterned electrode are fabricated by photolithographic processing of an indium tin oxide (ITO) film deposited on a glass substrate and consist of a circular array of rings. Both of the two electrode surfaces are coated with polyvinylalcohol as an alignment layer and are treated by rubbing to give a homogeneous molecular orientation. The refractive index experienced by the extraordinary beam is changed due to the reorientation of the LC molecule when a voltage is applied to the medium. The phase profile across

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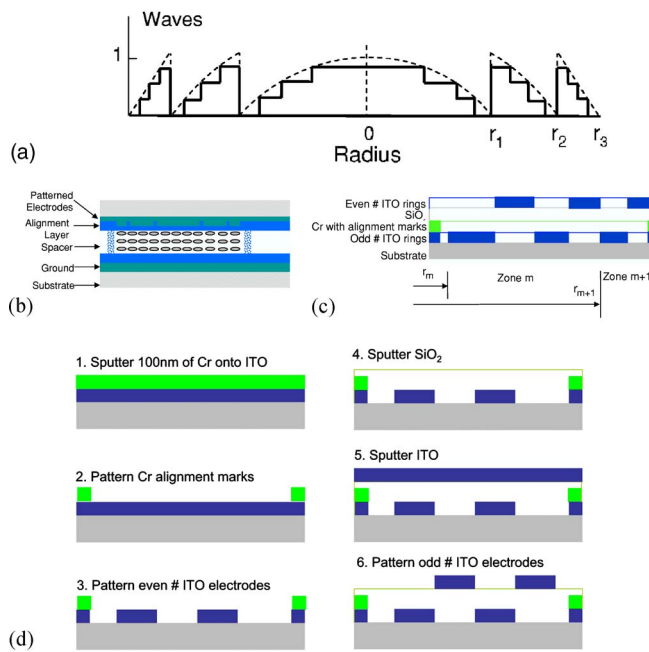


FIG. 1. (Color online) Switchable LC diffractive lens. (a) Phase profile of a diffractive lens. Dashed line, continuous quadratic blaze profile; solid line, four-level digitized phase profile. (b) Structure of the flat LC lens. (c) Structure of the two-layer electrode pattern. (d) Fabrication procedure for the interleaved electrode pattern.

the lens is tailored by applying proper voltages to the patterned electrodes and as such, determines the diffraction efficiency. 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 effects in the transition area of neighboring zones, and fabrication errors. The quantization error can be reduced by increasing the number of phase levels in each zone. For instance, an ideal diffractive lens with two- and four-level digitization corresponds to efficiencies of 40.5% and 81.1%, respectively. Simulations show that the gaps between the electrodes and different types of phase distortion at the electrode boundaries greatly affect diffraction efficiency and other performance parameters. 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 this demonstration, all the subzones having the same counting index n ($n=1, 2, \dots, N$) are connected together by a bus line, i.e., applied the same voltage, and thus have the same phase value. Figure 1(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. The fabrication procedure for the interleaved electrode pattern is illustrated in Fig. 1(d). With this design, it is easier to avoid shorts between neighboring ITO electrodes and fabricate lenses with larger aperture and smaller subzones.

Here, we demonstrate a four-level, 15 mm aperture lens with a 2 dpt focusing power at 555 nm, the peak of the human photopic vision response. The width of the last subzone at the edge is $9.2 \mu\text{m}$. After the lens is fabricated, various optical characterizations are performed. In the off state, transmission of the lens over the visible spectrum is above 85% if there is no antireflection coating on the surfaces. A polarized microscope is used to check the electro-optic function of each electrode. The lens is placed between two

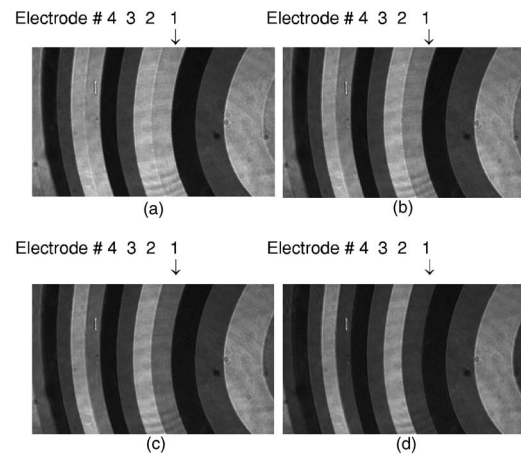


FIG. 2. Operation of the electrodes. Electrodes 2, 3, and 4 are set to certain voltages, respectively, while the voltage applied to electrode 1 was adjusted.

crossed polarizers, which are aligned with their transmission axes at 45° and -45° , respectively, to the horizontal axis. For each position, the intensity at the detector changes with the change of the phase difference (ϕ) between the ordinary and extraordinary components at the exit surface of the lens. The operation of each electrode can be inspected by observing the intensity variations over the area of said electrode. Figure 2 shows the intensity variation on electrode 1 when electrodes 2, 3, and 4 were set to certain voltages, respectively, and the voltage applied to electrode 1 was adjusted. The electrode boundaries can be clearly observed in the images.

To determine the diffraction efficiency as a function of lens area, the efficiency is measured for various beam sizes [Fig. 3(a)]. The efficiency for the 15 mm diameter area is above 75%. As we expect, the lens without gaps has only a little decrease in efficiency when the activated area increases. The decrease is because the phase distortion caused by the fringing field 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. Dependence of the diffraction efficiency on the incidence angle is related to the field of view effect for normal use of

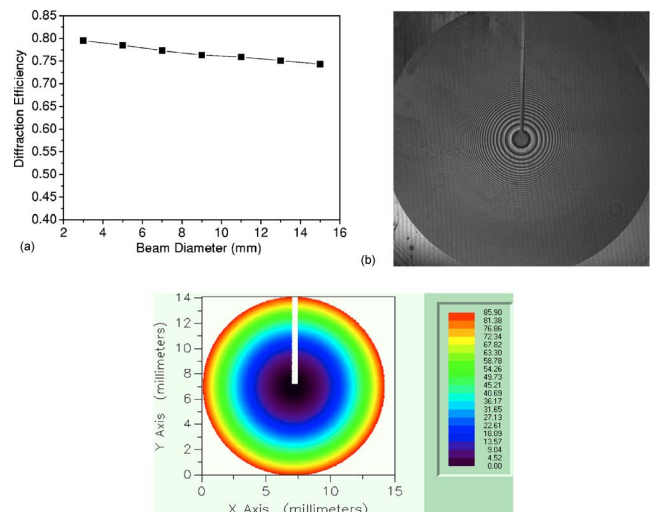


FIG. 3. (Color online) Some characterization results of the 15 mm aperture, four-level, 2 dpt lens. (a) Diffraction efficiency as a function of the beam diameter. (b) Interferogram obtained with the Mach-Zehnder interferometer. (c) Unwrapped phase map for a 14 mm aperture.

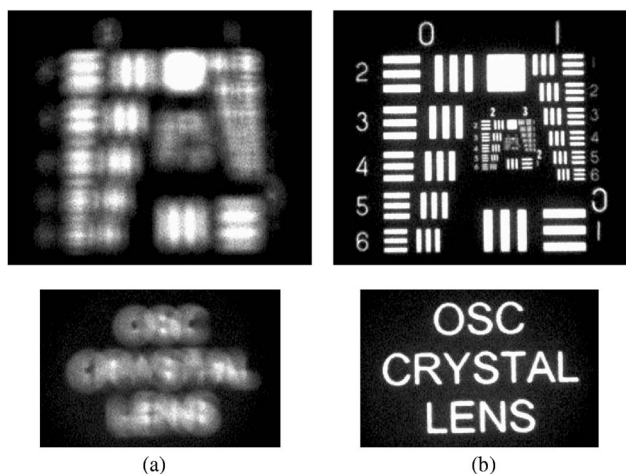


FIG. 4. Imaging using the 2 dpt electroactive diffractive lens with the model eye. The object is placed at a reading distance (~ 30 cm). (a) The image is severely out of focus in the model eye when the diffractive lens is OFF. (b) When the diffractive lens is activated, the object is imaged clearly.

the spectacle lenses. From the experiment, the diffraction efficiency decreases monotonically as the increase of the incidence angle. It drops about 4% when the lens is tilted 20° about the lateral axis.

A Mach-Zehnder interferometer operating at 543.5 nm was used to measure wave-front quality immediately behind the lens and to determine the focal length. The technique is based on interference between the spherical wave after the lens and a reference plane wave. Figure 3(b) shows an example of the measured interferograms. Five interferograms were taken with a phase shift between each interferogram and the wrapped phase map can be produced. The unwrapped phase map represents the actual optical path difference profile generated by the diffractive lens is shown in Fig. 3(c). A good spherical wave was obtained with very few higher order aberrations as indicated by a rms wave-front error of 0.0889λ . The focal length was found to be 50.855 cm, the focal length at 555 nm was calculated as 49.80 cm which corresponds to a focusing power of 2.008 dpt. The focused spot size was also measured and found to be $47.9 \mu\text{m}$, close to the diffraction-limited spot size of $45.1 \mu\text{m}$. The response time and the decay time were measured to be 180 and 120 ms, respectively. All these parameters indicate high performance of the lens. In addition, we also verified that, by changing the slope of the applied voltages to each zone, a negative 2 dpt focusing power can be obtained with the same lens, and the diffraction efficiency is the same as the positive 2 dpt case.

As nematic liquid crystal is polarization sensitive, two LC lenses with orthogonal alignment directions are required to form a complete lens that works for randomly polarized light. The double-element complete lens has been demonstrated to provide near vision correction for an accommodation-free model eye consisting of a 60 dpt refractive lens, an iris, and a charge-coupled device array. A white light source illuminates the object placed at a typical reading distance of approximately 30 cm. When the diffractive lens is not activated, the image is blurred [Fig. 4(a)], but when the diffractive lens is turned on, the object is imaged clearly [Fig. 4(b)]. The on and off states of the lens allow near and distance vision, respectively.

In conclusion, we have demonstrated a high-performance switchable electro-optic adaptive diffractive lens for vision correction of presbyopia. By interleaving the odd-numbered and even-numbered electrodes into two layers, there is no gap between the neighboring electrodes. This helps to maintain the desired diffraction efficiency and it makes it easier to fabricate lenses with large aperture and small feature size without shorts between the ring electrodes. Diffraction efficiency of above 75% has been achieved for four-level lenses with 15 mm aperture. This design methodology can be extended to phase steps larger than 4, where the electrodes can be addressed from an additional layer through vias. However, more fabrication steps are required. The focusing power of the lens can be adjusted to be either positive or negative, depending on the voltages applied to the patterned electrodes. Other advantages of this lens include compactness, lighter weight, low cost, and easier operation with low voltages and low power dissipation. For people who also need correction for distance vision, an additional refractive lens can be integrated with the switchable diffractive lens. Using nematic LC, two LC lenses set in orthogonal direction are required to make it polarization insensitive. In order to avoid light loss due to back reflections at the substrate interfaces, antireflection coating is necessary.

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