Switchable liquid-crystal lens could correct vision

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An electro-optic lens with voltage-controlled focusing power across the aperture takes a new approach to adjusting vision as people age.

More than 90% of people over 50 need correction for presbyopia, an age-related inability of the eye to shift focus from distant to near objects. Conventional lenses (bifocal, trifocal) have been used for more than 200 years, but they have drawbacks such as a limited field of view for each vision task. That requires users to gaze down for near vision, in some cases causing dizziness and discomfort. Some people need three different sets of eyeglasses for reading, computer use, and driving. Progressive lenses, or non-line bifocals, cause some distortion. However, an electro-optic lens uses voltage-control to change the focusing power across the entire aperture, removing these limitations and providing a new way to correct presbyopia.

We recently developed high-efficiency, switchable diffractive lenses and a prototype eyeglass based on a digitized-diffractive lens using a liquid-crystal (LC) active medium. The phase jump or transition at each zone boundary for the design wavelength is $2\pi$. To digitize this, we divided the continuous phase profile in each zone into subzones, with a series of discrete phase levels known as a staircase structure. Diffraction efficiency improves by increasing the number of subzones, reaching maximum values of 95% for lenses with eight phase levels per zone. Operation of these spectacle lenses is based on electrical control of the refractive index of a 5μm thick layer of nematic LC using a circular array of photolithographically defined, transparent indium tin oxide (ITO) electrodes. We have published two kinds of designs. In one, we patterned all the electrodes in one layer, and demonstrated eight-level, 1-diopter and 2-diopter lenses with an aperture of 10–15mm. In the other, the odd- and even-numbered electrodes are patterned separately in two layers with no gap between neighboring electrodes.

Figure 1 shows the electrode pattern. Using photolithographic techniques, concentric and rotationally symmetric transparent ITO electrodes were patterned on a float-glass substrate. Simulations of the effect of the inter-electrode gap shows a 1μm gap increase between adjacent electrodes to maintain electrical isolation and assure a smooth transition of the phases introduced by the LC. We sputtered an electrically insulating layer of silicon dioxide (SiO$_2$) over the patterned ITO and etched small openings in the via (a pad with plated holes) to allow electrical contact with the underlying electrodes. We subsequently sputtered an electrically conductive layer of ITO over the insulating layer to fill the vias and contact the electrodes. It was patterned to form eight independent electrical-bus bars. Each bus bar connected the discrete phase electrodes of equal counting index $n$ in all Fresnel zones, such that only eight external electrical connections (plus one ground connection) were required per lens. Figure 2 shows the structure of the LC lens. To form an LC alignment layer, we spin-coated polyvinyl alcohol onto the patterned substrate and another substrate with a continuous ITO electrode that acted as the electrical ground. We rubbed the layers with a velvet cloth to achieve homogeneous alignment, and assembled the two substrates. A commercial LC E7 nematic electro-optic

Continued on next page
medium from Merck & Co., Inc. was filled by capillary action into the empty cell at a temperature above the clearing point, then cooled to room temperature.

The lens performance was strong. For example, for a lens with a power of 1 diopter and an aperture of 10mm, eight optimized drive voltages produced a maximum first-order diffraction efficiency of 91%. The focused spot size is about 135µm, which is close to the diffraction-limit value. The switching time was 130ms. Interferometric measurements at 543.5nm showed excellent imaging capability. We obtained very good spherical profiles in both x and y cross sections, indicating small aberrations. We estimated higher-order aberrations by analyzing the difference between the measured wavefront and a best-fit spherical wave and tilt. The peak-to-valley range of the difference is 0.241λ and the root mean square is 0.039λ, which is comparable to high-quality reading glasses. The modulation transfer function indicated near-diffraction limited performance. The focusing power can be adjusted to be either positive or negative.

We recently demonstrated that based on this design, the focal length of the electro-optic lens can be switched between digital values by reducing the zone period. Each change corresponded to different diffraction efficiency, which allows near-, intermediate-, and distance-vision correction. For comparison, Figure 3 shows hybrid imaging using the switchable lens with a model eye, when the power of the lens is switched to plano (voltage off), 1 diopter, and 2 diopter. For the same condition, the 2-diopter LC lens would allow the model eye to see objects closer than the 1-diopter lens. The main effect on the image is the brightness.

These results represent important progress in advancing an adaptive lens for vision correction. These lenses showed high optical performance and can be used for multiple vision tasks. Astigmatism can be corrected by controlling the electrodes’ shape. Our future work will focus on developing a lens for multiple vision tasks with the same light efficiency. This will bring the technology closer to practical applications.

Figure 2. The structure of the adaptive liquid-crystal diffractive lens. V: Voltage.

Figure 3. Digital adjustment of the focusing power. Model eye imaging when the electro-optic lens is (a) voltage off, (b) switched to 1-diopter power, and (c) switched to 2-diopter power.

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Guoqiang Li, a faculty member, received a PhD from the Chinese Academy of Sciences and was a research faculty at the College of Optical Sciences, University of Arizona. He has published 75 refereed journal papers and two book chapters, and has delivered more than 20 invited presentations.

References


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