BY HONGWEN REN, YUN-HSING FAN,
YI-HSIN LIN, AND SHIN-TSON WU,
UNIVERSITY OF CENTRAL FLORIDA

Getting *in* Tune

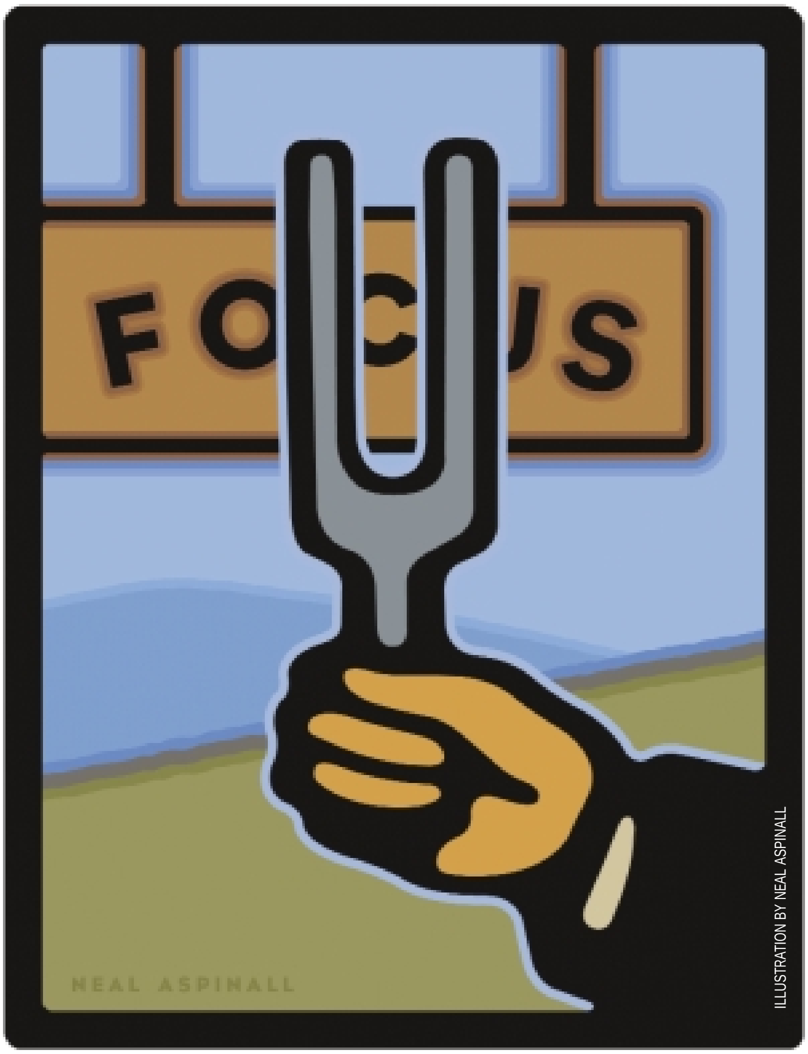

ILLUSTRATION BY NEAL ASPINALL

Electronically controlled liquid crystal yields tunable-focal-length lenses.

Lenses are key elements of optical systems. Most conventional lenses are made of glass, polymer, or other transparent solid materials. These lenses have fixed focus. To tune the focal length continuously, optical designers have developed the zoom lens, which consists of a group of lenses. Adjusting the distance between the lenses electromechanically varies the focus over a relatively large range. Zoom lenses can be effective, but the number of components involved makes them bulky and heavy. Many applications would benefit from a simpler, tunable-focus lens.

Tunable-focus lenses already exist in nature. The human eye, for example, is a single-lens system with a tremendously wide tunable focus range. The lens itself has a small refractive index gradient. The primary tuning mechanism is shape change, as controlled by the muscles in the eye. To mimic the foveated imaging of the human eye, researchers have developed several materials approaches, including liquids, microfluidics, polymers, and liquid crystals (LCs). Although the materials are different, the underlying mechanisms are similar, that is to generate and control the optical path difference between the center and edges of the lens through either shape change or refractive index change. Liquid lenses and microfluidic lenses are examples of using shape change, while LCs and stressed polymers are examples of using refractive index change.

Our group focuses on the tunable-focus LC lens. The major technical challenge of an LC lens is generating a gradient refractive index profile. Three fundamental approaches have been developed for demonstrating a tunable focus lens: an inhomogeneous electric field applied to an inhomogeneous LC layer, an inhomogeneous electric field applied to a homogeneous LC layer, and a homogeneous electric field applied to an inhomogeneous LC layer. Each approach offers benefits and challenges.

Inhomogeneous Electric Field Approaches

To form a tunable lens based on an inhomogeneous electric field applied to an inhomogeneous LC, we first deposit a top indium-tin-oxide (ITO) electrode on a concave substrate (see figure 1).[1,2] In the voltage-off state, the effective refractive index of LC material is n_e, which corresponds to a short focal length. An applied inhomogeneous electric field reorients the LC molecules perpendicular to the substrate. The effective index becomes n_o, which is closer to the

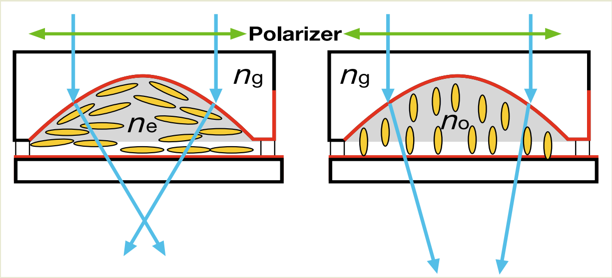

Figure 1 Applying an inhomogeneous electric field to an inhomogeneous LC layer changes the LC material from unoriented (left) to oriented (right). The refractive index change from that of the initial state (n_e) to that of the oriented state (n_o) changes the focal length.

refractive index of the substrate, n_g. The process thus increases the focal length.

The major advantages of this approach are twofold: The required operating voltage is low and the initial focal length can be relatively short. The LC molecules may not align well on the curved surface, however. In the thicker gap areas, light scattering could take place due to the director fluctuations.

We can also apply an inhomogeneous electric field to a homogeneous LC layer.[3] Two types of device configuration are considered here: modal lens and flat spherical lens. Each approach has its own merits and drawbacks.

The key element of the modal lens is the control electrode, which should have high sheet resistivity (5 to 9 MΩ/m) across the aperture.[1] Another critical component is a high-conductivity LC. The combination of high-resistivity transparent conductor and high-conductivity LC mixture allows us to generate a gradient electric field. The major advantage of this approach is that the required LC layer is thin enough to provide a very fast response time (about 30 ms). The high-conductivity LC conducts current, however, increasing power consumption. The flat spherical LC lens provides an alternative.

The flat spherical lens consists of planar substrates and a planar LC layer, but a spherical electrode.[4] To fabricate such an LC lens, we begin with a suitable plano-concave glass lens, and then overcoat the concave surface of the lens with ITO to form the electrode (see figure 2). We can match the sag area of the electrode with a convex lens of the same curvature or fill it with a polymer having the same refractive index as the glass substrate used to form the top planar substrate. The bottom substrate consists of flat ITO-coated glass.

For demonstration purposes, we filled the sag area with a UV curable prepolymer. To simplify the fabrication process, we used an empty LC cell to seal the prepolymer. The thickness of glass substrate that is in contact with the prepolymer is 0.55 mm, but without the ITO electrode. After UV curing of the polymer, the lens and the LC cell were attached together. The inner surfaces of the LC cell were coated with polyimide alignment layers and rubbed in an anti-parallel direction. The pretilt angle is about 3°. When an LC mixture was injected into the cell, homogeneous alignment was induced by the buffed polyimide layers.

Coating the inner surfaces of the two planar substrates with polyimide alignment layers produced homogeneous alignment of the LC. In the voltage-off state, incident light passes through the components without focusing. When a voltage is applied across the LC layer, the intensity of the electric field is the strongest at the borders and weakest in the center; thus, LC molecules present a centro-symmetrical gradient reorientation across the LC cell. As a result, the LC cell behaves like a positive lens. Controlling the applied voltage causes the profile of the refractive index distribution to change, altering the focal length.

Based on the aforementioned procedures, our group fabricated a spherical LC lens beginning with a 6-mm-diameter plano-concave lens (Edmund Industrial Optics; Barrington, NJ). The LC cell gap is about 40 µm. The birefringence of the nematic LC used is Δn=0.4. By adjusting the applied voltage, we can tune the focal length continuously from infinity at V=0 to 0.6 m at V=40 V_{rms}.

In comparison with other tunable-focus lens technologies, the flat spherical lens offers a simple fabrication process, simple electrode design, uniform LC cell gap, and plano-substrate surface. We can easily realize a negative lens with this technique by reversing the shape of the spherical electrode.

Homogeneous Electric Field Approaches

We can also produce a tunable LC lens using a homogeneous electric field.[5] Both approaches involve an inhomogeneous LC layer. Our group has considered two types of inhomogeneous cells: gradient polymer-network LC (PNLC) and

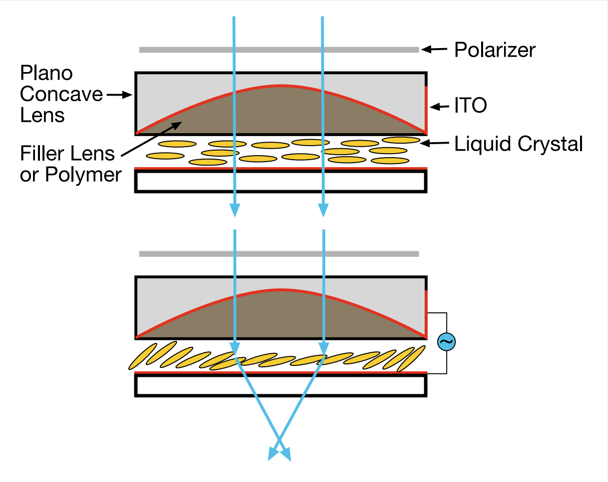

Figure 2 In the flat spherical LC lens, we mold an ITO contact, fill it with a lens or polymer, and then apply LC. The variation in contact thickness produces in an inhomogeneous applied field, converting the component from unfocusing (voltage off, top) to focusing (voltage on, bottom).

gradient refractive index nanoscale polymer-dispersed LC (GRIN PDLC) droplets. The PNLC approach exhibits a low operating voltage and relatively fast response time (about 30 ms), except that the device is dependent on the incident light polarization; therefore, in this article we only introduce the GRIN PDLC approach.

The phase-separation mechanism of the inhomogeneous PDLC differs from that of a conventional uniform-sized PDLC. To prepare an inhomogeneous PDLC, we used a centro-symmetric continuous variable-density filter as a photomask. The mask converts homogeneous UV input into an inhomogeneous output intensity. Photo-polymerization takes place preferentially in the high-intensity UV regions. The consumption of monomers in these regions lowers their chemical potential, which pushes the monomers to diffuse from the low- to the high-intensity region. At the same time, the LC molecules diffuse from the high- to the low-intensity regions to balance the chemical potential. As a result, an inhomogeneous PDLC sample exhibits gradient distributions, not only in droplet size but in concentration.

The region with larger droplet sizes also has a higher LC concentration. In the voltage-off state, therefore, the inhomogeneous PDLC sample exhibits gradient phase retardation. At V=0, the LC directors inside the droplets are assumed to be randomly oriented and the area with a larger droplet size will exhibit a higher refractive index. As the voltage increases, the refractive index decreases and the phase profile across the lens diameter is flattened. Finally, at $V=V_{\infty}$, the lens effect vanishes.

The GRIN PDLC effect offers three major advantages: polarization independence, low aberrations, and fast response times. The nanoscale PDLC droplets involved require drive voltages in excess of 100 V, and the optical phase change is relatively small. Small phase change leads to a long focal length, which is more suitable for telescope and satellite imaging applications. To achieve a shorter focal length, the lens aperture has to be reduced proportionally, for example in a microlens array.

Cylindrical Lenses

Another inhomogeneous approach involves cylindrical lenses. A cylindrical lens focuses light into a line, thus it can be used for stretching images, focusing light into a slit, or causing light to converge on a line-scanning detector. To obtain a variable focal length with wide aperture, we apply the slit electrodes to the outer surfaces of a planar LC cell (see figure 3). The two slits are parallel and symmetrical. The LC molecules are aligned along the slit direction. A voltage applied to the top and bottom electrodes generates an electric field that reorients the LC molecules between the slit regions. As a result, the gradient refractive index forms along the slit direction, focusing the incident linearly polarized light into a line.

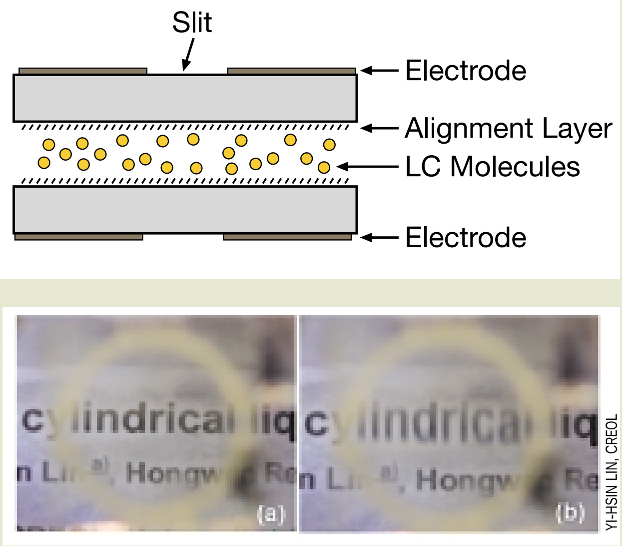

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Figure 3 By using slit electrodes (top), we can produce a cylindrical tunable lens (bottom).

Consider such a device with the cylindrical LC lens held at V=0 and V=180 V$_{rms}$, respectively. The LC cell gap is about 40 μm, substrate thickness 0.55 mm, slit width 2 mm, and LC birefringence Δn=0.4. At V=0, light is not focused. As the applied voltage is increased to 180 V$_{rms}$, the image through the slit region is elongated in one direction, demonstrating cylindrical lensing. The shortest focal length is about 5 mm at V=180 V$_{rms}$. Using this cell structure, we can enlarge the lens aperture by increasing the cell gap or by increasing the substrate thickness while keeping the focal length short. The increased operating voltage presents a tradeoff, however. To lower the operating voltage, one can use the cylindrical-shaped electrode similar to that shown in figure 2.

Tunable lenses based on LC technology can provide solutions for a wide range of applications. Depending on the application, homogeneous or inhomogeneous fields can work better. With improved performance over static lenses, tunable optics will offer an increasingly viable solution to engineering problems. **oe**

Hongwen Ren is a research scientist, Yun-Hsing Fan and Yi-Hsin Lin are graduate students, and Shin-Tson Wu is PREP professor at the College of Optics and Photonics, University of Central Florida, Orlando, FL. For questions, contact Wu at 407-823-4763, 407-823-6880 (fax), or swu@mail.ucf.edu.

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