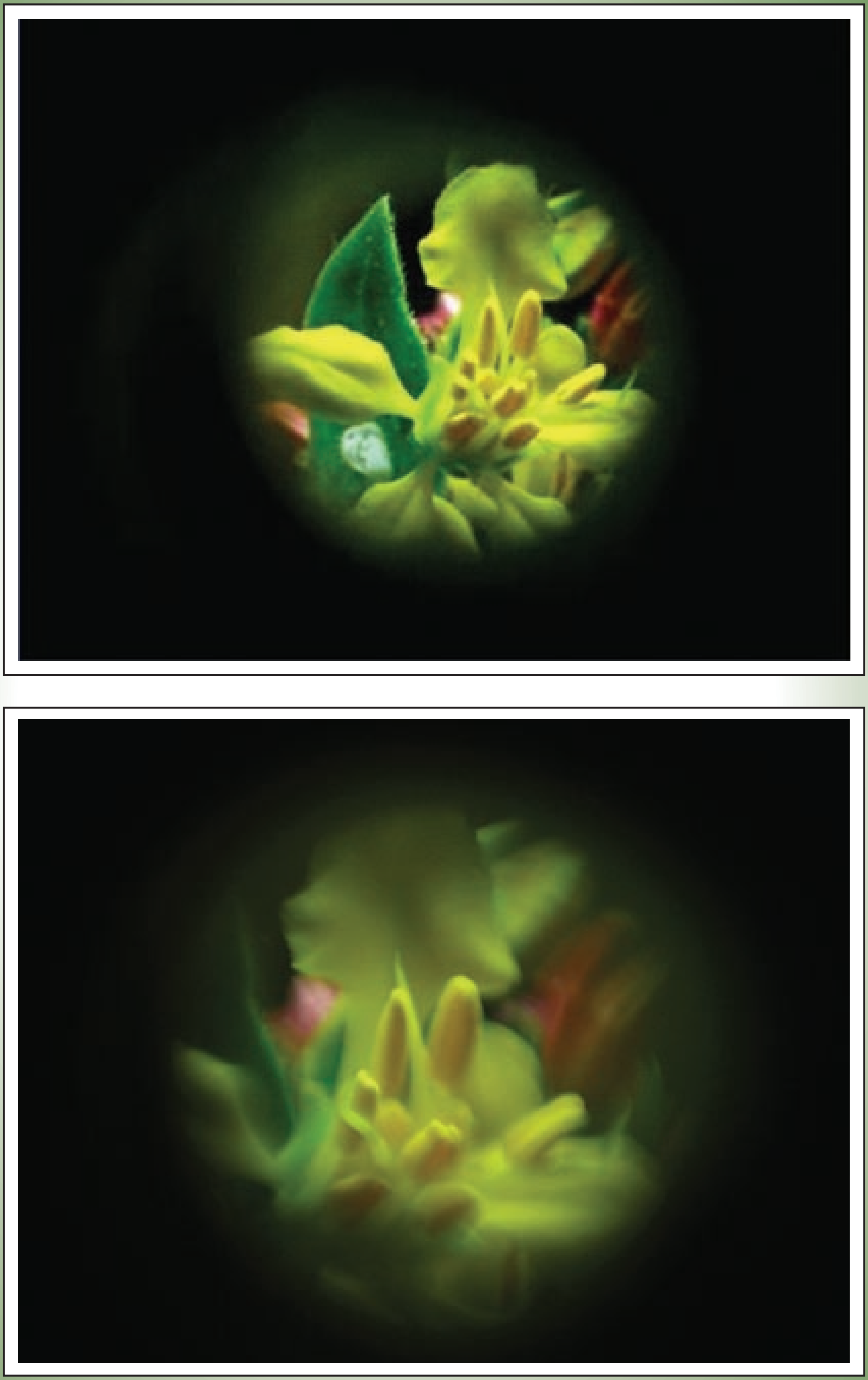

Image of a flower captured by an elastic membrane liquid lens in (top) a non-focusing state and (bottom) a focusing state.

Adaptive-Focus LENSES

Hongwen Ren, Su Xu, Yeong-Jyh Lin and Shin-Tson Wu

Researchers have recently demonstrated various approaches for constructing practical, compact adaptive-focus lenses. This article summarizes the advantages and drawbacks of each.

Imagine a lens that could adaptively change its focus power. Eyeglasses or contact lenses could have a built-in auto focus, and every cell phone might come equipped with its own zoom lens—not to mention more powerful applications in ophthalmology and medical imaging. For these applications to become reality, however, adaptive optical systems will have to shed their bulky, heavy and costly lens systems and complicated adjustment processes.

Several designs for compact systems are currently under investigation: liquid crystal (LC) lenses, elastic membrane lenses, electrowetting lenses and dielectric lenses.

Liquid crystal lenses

Nematic liquid crystals (LCs) are rod-like molecules. When aligned in a homogeneous cell, their long axes are approximately parallel to each other. The averaged alignment direction is called the LC director. Owing to the anisotropic dielectric and optical properties, the LC directors can be reoriented by an external electric field, which, in turn, causes phase retardation or phase change to the incident light. Phase retardation is useful for amplitude modulation—e.g., displays—where two crossed polarizers are commonly

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used. On the other hand, the gradient phase change that is induced by an inhomogeneous electric field is the foundation for the tunable-focus lens.

The concept of an LC lens was first proposed in 1977. Since then, researchers have demonstrated various approaches for constructing such a lens, such as using a surface relief LC layer, line- and hole-patterned electrodes, modal addressing, polymer-stabilized LC networks, and curved and flat electrodes. Each approach has its own unique features.

An LC lens with a hole-patterned electrode can be easily fabricated. The cell gap is uniform and the LC layer presents homogeneous alignment. When voltage is applied to the lens cell, a cone-shaped electric field is generated in the hole region. To ensure that the electric field can reach the hole center, the diameter of the hole should be comparable to the cell gap. For a thin cell gap, the diameter should be sub-millimeter size. Enlarging the hole diameter demands a larger cell gap, which subsequently increases the driving voltage and lengthens the response time. Moreover, the cone-shaped electric field can easily induce LC orientation disclination and thus degrade the lens quality.

Lenses based on modal addressing were proposed years ago. This approach has advantages in uniform cell gap, relatively low operating voltage, and fast response time. The focal length can be tuned, either by applying a fixed voltage but varying the frequency or by using a fixed frequency but varying the voltage. However, to generate a gradient electric field for the desired phase profile, the electrode must have a varying sheet resistance from edge to center. The fabrication process is rather complicated. Moreover, the LC material should have a high conductivity. As a result, power consumption and operation stability could be an issue.

Polymer stabilization is another interesting approach for making an LC lens. In the cell chamber of the lens, LC and polymer form a composite after ultraviolet curing. To generate the gradient refractive index required for a lens, one would typically use a special photomask with spatially varying transmittance. In the high transmittance area, the UV curing speed is faster, leading to a higher polymer network concentration or a smaller LC droplet size, depending on the polymer concentration.

When the polymer concentration is low, inhomogeneous networks are formed in the LC host. When one applies a uniform voltage across the cell gap, the area with a greater polymer network concentration exhibits a higher threshold voltage to reorient the LC directors. Thus, a gradient refractive index profile is formed.

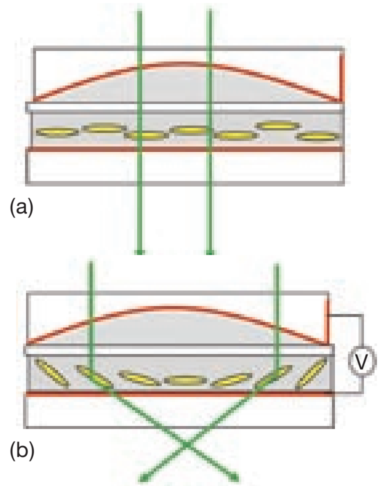
On the contrary, if the polymer concentration is high, LCs will form droplets in the polymer matrix with inhomogeneous size distribution. The larger LC droplets are easier to be reoriented than the smaller ones. Due to the stabilization or strong anchoring from the polymer surface, the response time of the LC lens is shortened significantly. The tradeoff is the increased operating voltage. Moreover, light scattering is induced by the refractive index mismatch between the LC and polymer binder.

Among all the approaches we've discussed so far, the lens with a shaped electrode and homogeneous LC layer is particularly attractive because of its uniform cell gap, freedom from light scattering, and scalable lens aperture.

To illustrate the lens operation principles, we will describe the lens cell with a curved electrode and a homogeneous LC layer. Part (a) of the top, center figure depicts the cross-sectional structure of such an LC lens. A homogeneous LC layer is sandwiched between two substrates, and the LC presents homogeneous alignment. The electrode deposited on the inner surface of the bottom substrate is flat, and the electrode embedded in the top substrate has a curved shape.

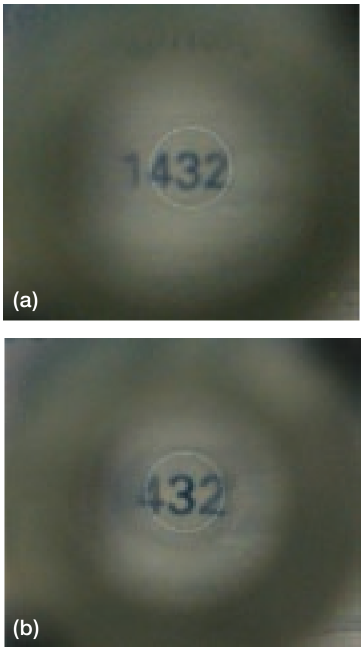
At null voltage, the incident light propagates through the LC layer without being focused. When a voltage (V) is applied across the electrodes, the LC layer

[Tunable-focus liquid crystal lens]



Tunable-focus LC lens with a curved electrode and a homogeneous LC layer in (a) a non-focusing state and (b) a focusing state.

[Imaging behavior of a liquid crystal lens]



Imaging behavior of a LC lens at (a) V=0 and (b) V=25 V_{rms}.

electric field is the foundation for the tunable-focus lens.

experiences a centro-symmetric inhomogeneous electric field. LC directors on the border experience a strong electric field and present a large tilt angle. On the other hand, the LC directors in the center bear a relatively weak electric field, so their tilt angles are very small. From border to center, a gradient refractive index profile is formed across the LC layer. As a result, the LC layer behaves like a converging lens. Its focal length can be tuned by the applied voltage.

The shape of the top electrode affects lens performance. In our studies, we found the parabolic electrode shape produces the shortest focal length. The bottom figure on the facing page shows the images of an LC lens in the voltage-off and voltage-on states. At V=0, the size of the image is almost the same as the object. When a voltage is applied across the LC layer, the observed object is magnified. Because the object is placed within the focal length of the lens, the observed image is upright but virtual. The enlarged image is as clear as the object.

Unlike a glass lens, most LC lenses are polarization-dependent. To overcome the polarization dependence, one could consider using two devices stacked in orthogonal directions. Slow response time poses another technical challenge. It is the inevitable result of using a thick LC layer to obtain the short focal length needed for a large-aperture (5 mm) lens. Therefore, LC lenses are more suitable for microlens applications. Moreover, the phase profile of a simple LC lens is hardly spherical, so its resolution is limited. This type of lens is intended for low-cost camera-zoom applications. For ophthalmology, a high-resolution LC spatial light modulator with individual pixel control capability is a better option.

Elastic membrane lenses

Adaptive liquid lenses based on elastic membranes were developed decades ago. Since then, researchers have made many efforts to improve the lenses' structure and performance. Compared to LC lenses, membrane lenses have better image quality, a larger aperture, wider focal length tunability and broader bandwidth. They are also polarization-independent.

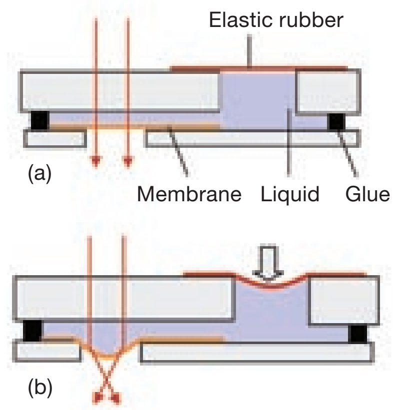
In the lens cell, a liquid is sandwiched between two substrates, and the periphery of the two is sealed with glue. At least one substrate is made of an elastic membrane. Usually, the lens chamber is connected with a mechanical pump through a connecting pipe. By pumping liquid in or out of the lens chamber, the surface of the elastic membrane turns to a convex or concave profile. Thus, the cell functions as a lens, and the focal length is variable.

Because it requires a pumping machine, the whole lens system is bulky and costly. Recently, researchers proposed a revised lens structure with a variable focal length that did not need a mechanical pump. In this approach, a liquid with a fixed volume is sandwiched between two slabs, and the periphery of the slabs is sealed with glue. Each slab has a hole, and the two holes are sealed with elastic membranes. Without an external force, the elastic membrane of the lens cell is in a flat state. When external pressure is applied to deform the outer elastic rubber inward, the liquid in the lens chamber is redistributed, causing the inner elastic membrane to swell outward. The resultant lens is plano-convex and the incident light is focused.

To drive this kind of lens, one can use a battery-powered piezoelectric stack actuator, a servo motor or artificial muscles to squeeze the top elastic rubber. The operating voltage is low and the power consumption is mainly dependent on the periphery electronic device.

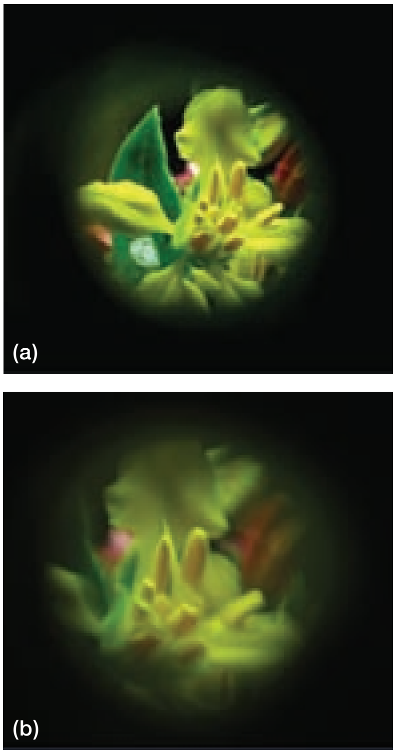
In a lens cell, the elastic membrane is the key part. Usually, polydimethylsiloxane (PDMS) is the preferred material for elastic membranes. It is highly transparent in the visible range, with large elongation and bio-compatibility. In practical applications, the thickness of the PDMS membrane is controlled at 50-100 μm because a too-thin membrane will become permeable to liquids. To obtain a large dynamic range, it is

[A liquid lens]



Side view of a liquid lens in (a) a non-focusing state and (b) a focusing state.

[An elastic membrane liquid lens]



An elastic membrane liquid lens in (a) its non-focusing state and (b) its focusing state.

best to use a liquid with a high refractive index that is colorless and non-poisonous. Also, it should not react to or swell the PDMS membrane.

We prepared a liquid lens with a 5-mm hole diameter, a 1-mm gap between two slabs, and a 100-µm PDMS membrane. The liquid we used was water. To evaluate the image performance, we set the lens cell in a vertical direction and placed a small flower behind it. In the non-focusing state, the observed image has the same size as the object. When a pressure is applied to the reservoir hole, the lens starts to focus.

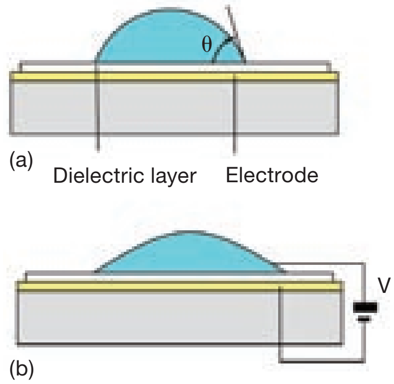
Similar to other liquid membrane lenses, the swelled membrane surface is not spherical and even the apex distance is very short. This is because the deflection of the PDMS membrane is nonlinear. As the membrane deformation increases, the gravity effect becomes more noticeable and eventually causes severe lens aberration. In practical applications, it is still a challenge for the membrane lens to function without the influence of gravity.

Electrowetting lenses

When an electrically conducting liquid drop falls on a solid surface and has a contact angle on the surface, the contact angle can be tuned if a suitable voltage is applied across the liquid, and a counter-electrode is placed underneath the solid surface. Berge studied this phenomenon in detail in the early 1990s. Since then, researchers have developed numerous device approaches based on the electrowetting effect. Here, we focus on the device structure and operation mechanism of electrowetting lenses.

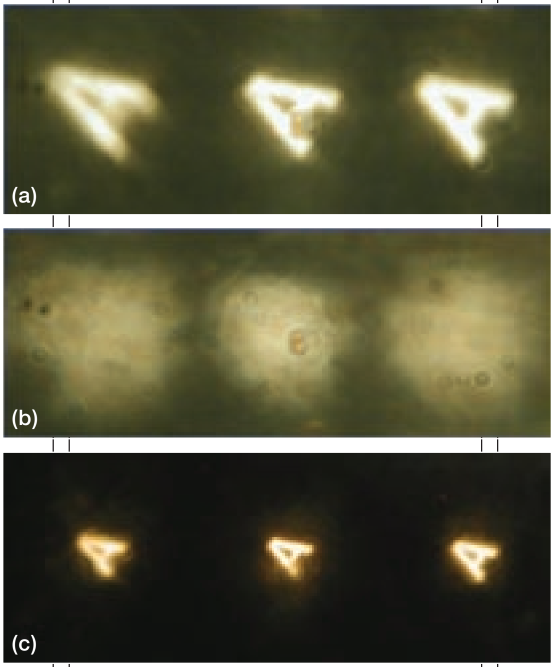
The schematic at the top, center of the page depicts the side view of a liquid electrowetting lens. A conducting liquid and an electrode are separated by a thin dielectric layer. Because the surface tension of the dielectric layer is weak, the liquid partly wets the surface and forms a drop with a contact angle to the surface. The contact angle of the

[An electrowetting device]



Side-view structure of electrowetting device. Conductive liquid droplet at (a) V=0 and (b) with an applied voltage.

[Performance of a dielectric liquid lens]



Imaging performance of a dielectric liquid lens (1 × 3 microlens array) at (a) 0 V, (b) 60 V, and (c) a re-focused state at 60 V.

droplet is determined by the interfacial surface tension between the dielectric layer and the droplet, the droplet and the surrounding gaseous phase, and the surrounding gaseous phase and the dielectric layer.

When one applies a voltage across the droplet and the counter-electrode, the dielectric layer bears a voltage and functions as a charged capacitor. To minimize the energy, the droplet will spread over a wider area, and the contact angle decreases correspondingly. This will re-balance the interfacial energies and lead to a shape change of the droplet. Removing the voltage discharges this dielectric layer capacitor and returns the droplet to its original state.

A liquid lens with such a structure can work well when the droplet is tiny, because the effect of gravity is negligible. When the droplet is big enough, however, the gravity effect becomes a concern. This is because, when the droplet is placed upside down or in a vertical direction, the gravity force will deform the shape of the droplet or change its position. To avoid this, another liquid should be used. In an electrowetting lens, usually salt-doped water is used as the conducting liquid and non-polar oil balances the gravity effect. The oil material that is used should be immiscible with water, have the same density as water, and be optically transparent and non-harmful.

Research has shown that the lens can be switched over a long period without any degradation in performance. For a lens with a 3-mm inner diameter, the focusing power can be controlled between –100 and +50 diopters, and the response time is as fast as 10 ms. Compared with elastic membrane lenses, the electrowetting lenses have two advantages: First, they are insensitive to shocks and vibrations due to the density matching of the two liquids and, second, they have a very smooth liquid surface (on a nanometer scale) due to surface tension.

Therefore, electrowetting lenses can provide much higher optical quality than other liquid lenses. Because two liquids are involved in the lens cell, the cell gap of the lens should be thick to avoid the capillary effect when one is making a large aperture lens. A typical operating voltage for an electrowetting lens is about 60 V. For practical applications, this operating voltage should be decreased further.

Dielectric lenses

Dielectric lenses have some of the same features as electrowetting lenses. For example, they use two different liquids and have a similar lens structure and electrical driving. They also have a large focus power change and fast response time during focus change. However, the two liquids in dielectric lenses are nonconductive, immiscible, and have different dielectric constants and refractive indices. Dielectric lenses with nonconductive liquids have the advantages of low power consumption, high voltage stability and no air bubbles.

When the contact interface of the two liquids experiences an inhomogeneous electric field, the generated dielectric force causes the low dielectric constant liquid to shrink toward the region where the electric field is weaker. The contact surface profile of the two liquids can be reshaped and, as a lens, its focal length is tuned correspondingly.

There are two methods for obtaining an inhomogeneous electric field: One is to use a zone-patterned indium-tin oxide (ITO) electrode and the other is to use a hole-patterned electrode. The lens with a zone-patterned ITO electrode is suitable for large apertures, while the lens with a hole-patterned electrode works best for small sizes and microlens arrays.

In terms of performance, dielectric lenses can be just as good as electrowetting ones. For example, the bottom figure on the facing page illustrates a 1×3 dielectric microlens array. The lens aperture is 140 μm and the two liquids used are de-ionized water and diacrylate monomer. To characterize image performance, a letter “A” typed on a piece of transparency is placed under the lens array as an object. By adjusting the distance between the lens cell and the object, one observes a clear image. In contrast to the original object, the image of “A” is inverted. When a 60 V (at 300 Hz) voltage is applied to the cell, the images are totally blurred because of the highly de-focusing effect. To restore clarity, the cell position must be adjusted while the same voltage is still on the cell. After being re-focused, the images are still very clear except for the reduced size.

The tunability of the lens shape is dependent on the dielectric force generated in the interface of the two liquids. Moreover, dielectric force mainly depends on the gradient of the electric field and the difference between the dielectric constants of the two liquids. Therefore, when designing a dielectric lens, one should consider the gradient of the electric field and the difference of the dielectric constants. To realize a lens with large dynamic range, one should choose two liquids with a large refractive index difference as well.

Concluding thoughts

Of the adaptive lenses we have discussed, liquid crystal lenses are perhaps the most suitable for making small aperture lenses. Because this lens is based on the gradient refractive index change, its phase difference between the lens center and edge is relatively small, on the order of a few tens of micrometers. In addition, liquid crystal lenses are easy to fabricate and have good long-term stability and low power consumption. However, most liquid crystal lenses are sensitive to light polarization, wavelength and operating temperature because of the phase retardation effect. The response time of a liquid crystal lens depends on the LC layer thickness. A thick LC layer, which leads to a slow response time, is needed to obtain a large dynamic focus change.

On the other hand, each of the three types of liquid lenses we described (elastic membrane lenses, electrowetting lenses and dielectric lenses) offer a tunable focus through shape change, similar to a human eye. The shape change provides a large optical path-length change, on the order of millimeters. As a result, the lens aperture can be made large while preserving a wide dynamic range. Moreover, liquid lenses are polarization-independent and have the potential for achieving video rate response time. The electrowetting and dielectric lenses offer a very high resolution, which is desirable for precision optical systems. However, the operating voltage needs to be reduced before widespread applications can be realized.

OSA Member

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