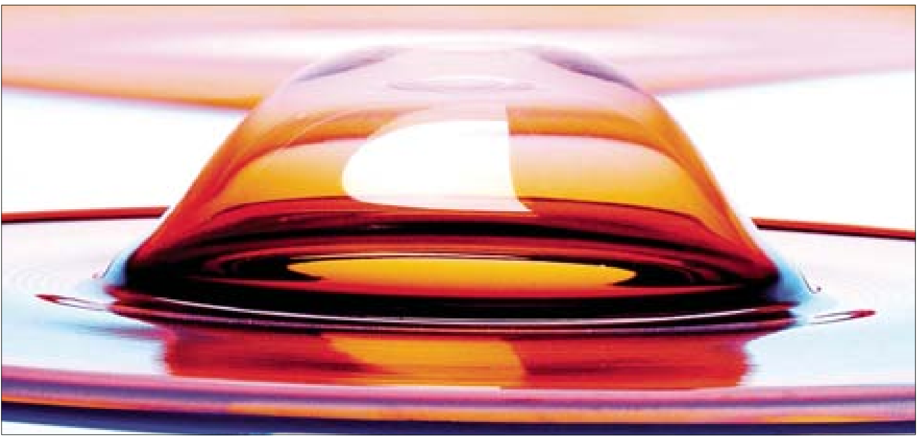
Liquid lenses shape up

Researchers are developing lenses that can alter their focal length in response to changes in their environment. **Hongrui Jiang** and **Liang Dong** provide an insight into the field.



Research groups globally are pioneering different ways to change the focal length of a liquid lens.

If you wear glasses and want to protect your eyes from harmful ultraviolet rays when you step outside into bright sunshine, you can do a number of things. You can switch to a pair of prescription sunglasses or don some clip-on shades. Alternatively you can invest in a pair of glasses with "photochromic" lenses, which go dark in strong sunlight. These lenses contain silver compounds that react when exposed to ultraviolet light, which means they absorb energy from the light and therefore go dark.

Such lenses are said to be "smart" because they can adapt to their environment without human intervention. An example of a more complex smart system is the adaptive optics used by astronomers to image faint objects. The system compensates for the distorting effect of the atmosphere by first measuring how much a uniform light wavefront is perturbed and then applying an opposite distortion, usually by making the appropriate changes to a deformable mirror.

Now, physicists are starting to develop "adaptive lenses" made from liquids or soft polymer materials that can change their focal length in response to external stimuli. At varying degrees of commercialization, these devices hold great promise in imaging applications where space is at a premium, from mobile-phone cameras to surgical endoscopes.

The lure of liquids

One way to make adaptive lenses is to control the refractive index of a layer of nematic liquid crystal, a substance that flows like a liquid but consists of long molecules that line up in the same direction. The basic design involves placing a layer of liquid crystal between a hemispherical electrode and a planar electrode (see figure 1a). When a voltage is applied, the electric field varies symmetrically about the centre of the electrodes – being highest at the edge and lowest at the centre. Since the refractive index of the liquid crystal depends on the orientation of the molecules, and the orientation of the molecules changes with the electric field, the varying field sets up a corresponding variation in refractive index. The liquid-crystal layer therefore acts like a lens, with light passing near the edge of the device being bent more than light near the centre. The focal length of the lens depends on the voltage that is applied.

Such liquid-crystal lenses have been developed by a number of research groups, including one led by Shin-Tson Wu at the University of Central Florida, US, in 2004. A similar technique was used this year by Guoqiang Li, Nasser Peyghambarian and co-workers at the University of Arizona, US, to make a prototype device to replace the multifocal lenses used by long-sighted people. But there are problems associated with these devices, including astigmatism (which means the lens cannot focus properly), distortion and light scattering when the focus of the lens is changed.

Earlier this year, however, Wu and colleagues came up with a different approach to liquid-crystal lenses that gets round some of these problems (see figure 1b). The same arrangement of electrodes is employed, but in this case it is used to vary the distribution of monomer molecules that have been mixed in with the liquid crystal (the liquid crystal having been chosen carefully so that its molecules do not rotate in the presence of the field). Without any voltage, the two types of molecules are mixed up uniformly and do not focus light. But in the presence of a voltage, the liquid-crystal molecules are attracted towards the region of greatest field strength – the edge – and the monomer molecules diffuse towards the centre. This sets up regions of higher and lower refractive index at the edge and centre, respectively. In other words, it acts like a lens.

Another way to make adaptive lenses is simply to use liquid droplets. Readers will know that a water droplet on a piece of paper can magnify the text on that paper. Here, the curved meniscus of the liquid bends, and therefore focuses, light – forming a lens with a focal length that depends on the curvature of the droplet. To control this focal length to make a tuneable liquid lens, we need to modify the molecular forces that hold the drop together in the first place – the surface tension.

Modifying surface tension

One way to do this is to use simple mechanics. Earlier this year, for example, Saman Dharmatilleke, Isabel Rodriguez and colleagues at the Institute of Materials Research and Engineering in Singapore filled a tiny well made from a polymer substrate with a liquid such as water (see figure 1c). They showed that by varying the pressure on the droplet, the curvature of the meniscus can be changed and hence also the focal length of the droplet. This technology is being commercialized for use in mobile-phone cameras, since the camera lens can be refocused directly by the pressure exerted on a keypad. This does away with much of the motor circuitry needed to focus a solid lens and hence makes the focusing system more compact and lightweight.

But the curvature of a liquid droplet can also be changed electrically, as demonstrated by Stein Kuiper and co-workers at Philips in 2004. The researchers lined the inside of a glass tube with a coating that repels water and then filled the tube with an aqueous salt solution and silicone oil. With no voltage applied to the tube, the salt solution is pushed down the walls of the tube

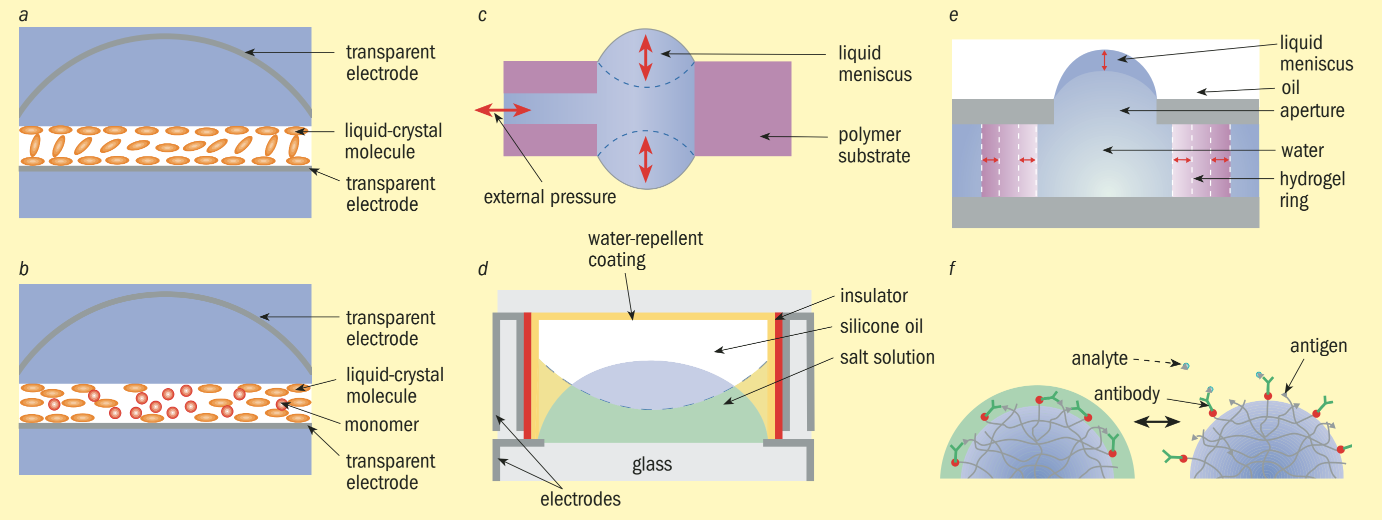


Fig. 1: there are several different ways to make a lens with a tuneable focal length: a variation in the refractive index of a layer of liquid crystal can be achieved either by varying the orientation of the liquid-crystal molecules (a), or by varying the concentration of these molecules (b). Alternatively, the shape of a liquid drop can be controlled by changing the pressure exerted on it (c), or by electrically varying the surface tension between it and the side of a glass chamber (d). Finally, a polymer known as hydrogel can be used either in a physical system, in which an expanding hydrogel ring creates a meniscus at a water–oil boundary (e), or in a biological system, in which a drop of hydrogel changes its density, and hence optical properties, through a reversible antigen–antibody reaction (f). Devices (a) to (e) are all of the order of 1–10 mm across, while (f) is about 2 μm across.

and therefore bulges in the middle, taking on a hemispherical shape (see figure 1d). But with the voltage switched on, the coating becomes less water-repellent and the salt solution climbs up the walls, assuming an inverted spherical shape (represented by the dotted line in the figure). Since the refractive indices of the salt solution and the oil are different, a change in the shape of the boundary between them alters the focal length of the lens. Researchers have shown that this type of lens could also have applications in digital cameras, as well as for "electronic paper", a flexible substrate that can display a continually updated image. In

the latter, each pixel would contain a liquid lens, with the layer of coloured oil made to move around the cell in such a way that it allows more or less light through (corresponding to a dark or light pixel).

Truly adaptive

The lenses described so far are not adaptive in the strict sense because they rely on external sensors to provide the feedback information. Recently, however, researchers have developed lenses that act as their own sensors. For example, earlier this year the authors of this article plus two other colleagues at the University of Wisconsin-Madison showed how polymers known as responsive hydrogels can convert environmental changes into mechanical work. These materials expand or contract when subject to different chemical, biological and physical stimuli – such as temperature, acidity and electric field.

To make our lens, we built a ring from hydrogel and filled it with water. A cover with a hole in the middle was placed over the water. The top of the cover was smeared with a substance that repelled water, while the rim of the hole was lined with a material that attracted water (see figure 1e). As a result, when oil is poured onto the cover and the hydrogel expands due to external stimulus, the water is pushed up through the hole but pinned at its edge to form a well-defined meniscus. So, like the muscle in the human eye, the hydrogel changes the focal length of the lens when subject to external stimuli.

Another intriguing example of a "smart" lens was demonstrated this year by Andrew Lyon and co-workers at the Georgia Institute of Technology, US. In this case, the surface of a drop of hydrogel is covered with specific pairs of antibodies and antigens (see figure 1f). In the drop's default state, the antibodies and antigens are bound to one another to create a high-density halo around the drop. But in the presence of specific "analyte" particles, the antibodies and antigens become unbound, the high-density halo disappears, and the refractive index – and therefore the focal length – of the drop changes. The lens could be used as a sensor, with many such devices deposited around a cell to measure how many molecules of a certain protein are interacting with that cell.

Despite these advances in controlling the focal length of a lens, the field of smart optics is still relatively new. Further work is needed to convert these devices into sophisticated adaptive systems. In particular, most adaptive lenses need to be able to focus far more quickly and be more mechanically robust in order to operate in harsh environments such as the desert, space and in moving vehicles. However, progress will continue to be made. For example, the liquid-crystal lenses being developed by Wu and colleagues take about three minutes to change focus. This is because the lens is relatively large – 9 mm – which means that molecular diffusion across it is slow. But with lenses measuring just 50 μm across – which should be possible to achieve using current microfabrication technologies – the estimated response time is about 1 s at room temperature. Who knows, maybe in the near future, when you step back inside your house after the Sun has set, your glasses will be equipped with sensors that immediately detect how dim the room is and then automatically switch on the lights at the right level. Welcome to the brave new world of smart optics. □

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This article was originally published in the November issue of *Physics World*.