possibilities for such devices in general. In particular, omnidirectional retroreflectors are likely to find use wherever back-reflecting mirrors are required whose alignment is hard to fix.

Although perhaps less striking in its physical effect than a perfect lens or an invisibility cloak, the work of Ma *et al.* demonstrates that other devices hitherto confined to theory can be practically constructed. Of course, the field of metamaterials is so vibrant partly because old theoretical suggestions, such as that of Eaton here, or Veselago for negative refractive index[11], are now being physically implemented by a synthesis of new theory and experiment. Many other possibilities for metamaterials have been suggested. Now that even singularities in refractive index are no longer an obstacle towards their implementation, only time will tell as to which of these will be engineered into optical devices. ❐

Mark R. Dennis is in the H H Wills Physics Laboratory, University of Bristol, Tyndall Avenue, Bristol BS8 1TL, UK.
e-mail: mark.dennis@bristol.ac.uk

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LIQUID CRYSTALS

Printed actuators in a flap

Solid liquid crystals couple orientational order and mechanical strain, enabling fundamentally new mechanisms of actuation. Depositing the materials using inkjet printing allows precise control of their shapes and composition, producing devices with new microfluidic applications.

Peter Palffy-Muhoray

In spite of impressive demonstrations of the potential of soft polymeric materials for actuator applications[1], key obstacles to the construction of practical all-polymer devices remain. The continuing need for large shape changes and complex motion, which in turn requires precise control of sample shape, material structure and composition, as well as effective addressability and efficient energy transfer, all impede further development. However, innovations that make fresh use of existing technologies can be remarkably effective in advancing a field, as shown by Galileo's use of optical lenses to make a telescope. On page 677 of this issue[2], the team of van Oosten, Bastiaansen and Broer at Eindhoven University of Technology propose an elegant scheme using self-organizing liquid-crystal inks and inkjet printers together with photoaddressing to produce miniature actuators. These 'artificial cilia' can be made to flap by irradiating them with light to drive flow in microfluidic devices.

Liquid crystals are characterized by the long-range orientational order of their constituents; typically, rod-like molecules align parallel to one another in a liquid phase. As temperature is increased, thermotropic liquid crystals undergo a phase transition to an isotropic fluid phase as orientational order is lost. In 1975, de Gennes suggested that combining liquid crystallinity with polymer networks[3] would result in a coupling between orientational order and mechanical strain. In 1981, Finkelmann produced the first liquid-crystal elastomer[4], an elastic solid, consisting of a weakly crosslinked polymer network with mesogenic side chains having nematic order. As predicted by de Gennes, increasing the temperature decreases the degree of orientational order. This reduction in order causes a contraction of crosslinks — and hence of the material — along the alignment direction, and an expansion in the perpendicular directions.

This change in the degree of alignment resulting in strain forms the basis of the actuation in the work of van Oosten and colleagues. To increase the capacity of the material to do work, the group used a more highly crosslinked network, with elastic modulus in the gigapascal rather than the more common megapascal range. Instead of changing the temperature to alter the degree of order, they incorporated azobenzene moieties in their network (Fig. 1). In their elongated *trans*-state, these align with the oriented mesogens, but when irradiated with light, they undergo photoisomerization to a strongly bent *cis*-state, reducing the degree of nematic order just like an increase in temperature. This photoactuation scheme provides an effective way of transferring energy to the working element without the need for compliant electrodes and wires, as in the case of electrically driven systems. It also allows for spatial addressing simply by using different azo dyes, with absorption for photoisomerization at different

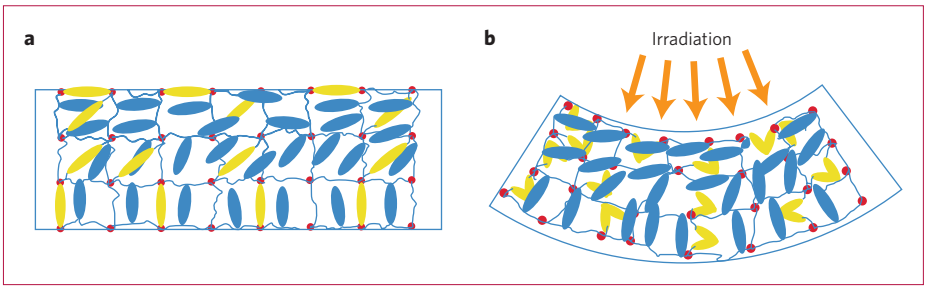

Figure 1 | Mechanism of light-induced bending in a liquid-crystal elastomer. **a**, Mesogenic units (blue) and azo-crosslinker (yellow) in the *trans*-state align parallel. **b**, On irradiation with light, the crosslinker undergoes *trans–cis* isomerization, contracting the network in the horizontal direction on top, and dilating it on the bottom, causing bend.

wavelengths, in different parts of the actuating element.

To achieve complex motion beyond simple contraction and extension, the Eindhoven group used an ingenious alignment configuration: the direction of mesogen orientation changes smoothly and continuously from parallel to the surface on one face of the actuator element to perpendicular on the other. Photoexcitation causes contraction of the material on one surface and expansion on the other, as in a bimetallic or birubber[5] strip. This architecture allows large bend deformations even if the photoexcitation is uniform everywhere in the actuator material. More complex motion is made possible by the use of different azo dyes in different regions of the actuator strip. Illuminating the entire strip with light of a given wavelength results in bending only where the light is absorbed. Bend in different regions can be controlled independently by simply changing the wavelength.

One of the proposed applications for these actuators is pumping and mixing in microfluidic systems. Here, small length scales result in flow in the Stokes regime, where viscosity dominates and inertial effects are negligible. As shown by Purcell in 1976, this is the domain of the scallop theorem, in which swimming — or equivalently, the pumping of fluid — is impossible with motion where the sequence of configurations is indistinguishable from the time-reversed sequence[6]. As Purcell put it, "a scallop opens its shell slowly and closes its shell fast, squirting out water" to swim, but in the Stokes regime, "it can't swim"; the scallop gets nowhere if it tries to swim in treacle.

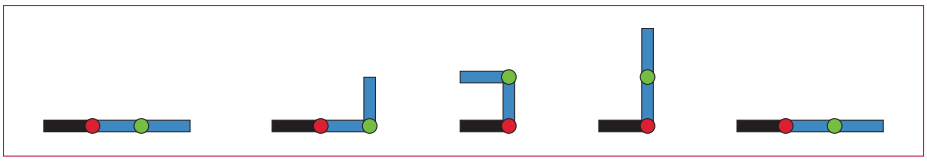

Figure 2 | Non-reciprocal motion made possible by two bend regions of the actuator. The black segment is attached to the substrate.

The cilia proposed for pumping by van Oosten and collaborators have two distinct and separately addressable regions for bend (Fig. 2). Activating these in sequence means the motion is non-reciprocal, and the cilia are therefore capable of pumping fluid.

The elegant solutions to the problems of realizing effective actuators proposed by the Eindhoven group are orientational order that varies spatially, the incorporation of different azo compounds in different regions of the active material and careful control of actuator shape. These stringent requirements would seem to make practical production prohibitively complicated. Evidently, this is not the case. The Eindhoven group used inkjet printing with self-assembling liquid-crystal inks on substrates and patterned sacrificial layers to produce the required spatially varying orientational order and composition. These printed liquid structures are then crosslinked through photopolymerization, and, on dissolving the sacrificial layers, become photoactive cilia attached to the substrate. Because of this remarkable demonstrated versatility, printing with liquid-crystal inks holds the promise of enabling the production of a variety of other new active polymeric microdevices. ❐

Peter Palffy-Muhoray is at the Liquid Crystal Institute, Kent State University, Kent, Ohio 44242, USA.
e-mail: mpalffy@cpip.kent.edu

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IRON-BASED SUPERCONDUCTORS

Vital clues from a basic compound

Investigation of the phase diagram of the structurally simple compound FeSe may prove instrumental in raising the transition temperature in Fe-based superconductors and in understanding magnetic-mediated superconductivity.

Bernd Büchner and Christian Hess

One of the greatest ambitions of solid-state physicists has been to obtain superconductivity — a macroscopic quantum effect leading to the flow of electrical currents without dissipation — at technically relevant temperatures. For more than 20 years, the efforts have focused on understanding the properties of the so-called cuprate superconductors. These compounds show superconductivity at temperatures that are in some cases higher than that of liquid nitrogen (77 K), and it is clear that the origin of superconductivity is different than in the case of low-temperature — or conventional — superconductors. Then suddenly, in the spring of 2008, the discovery of superconductivity below a critical temperature (T_c) at 26 K in $LaO_{1-x}F_xFeAs$ (ref. 1) gave birth to what many have already christened "the iron age of high-temperature superconductivity". Some 1,000 papers later, a whole class of iron-based high-temperature superconductors has been established.

The members of the iron-pnictide superconductors share a common structural motif, namely layers with edge-shared tetrahedra, whereby the central Fe atoms are surrounded by four As, P or Se atoms, respectively. The Fe_2X_2 (X = As, Se) layers are considered to be electronically active, whereas the other layers stabilize the structure and serve as charge reservoirs to dope the active layers. Many specific characteristics and problems observed in the pnictides, such as, for example, chemical complexity and phase separation, are closely related to these extra structural elements. Recently however, superconductivity was observed in the basic structure FeSe, which consists