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Micron-sized liquid crystalline elastomer actuators

Hong Yang,^a Gang Ye,^b Xiaogong Wang^b and Patrick Keller^{*c}

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Over the last few years, following a trend to miniaturization found in many fields of materials science, micron-sized liquid crystalline elastomer (LCE) actuators have been described, with the aim to apply them in such domains like responsive surfaces, microfluidic devices or microsensors. The preparations of the micron-sized LCE actuators involve plenty of cutting-edge, advanced technologies such as soft lithography, microfluidic, microprinting or photomasking. In this highlight, we describe the most striking results obtained in the domain of micron-sized LCE-based responsive systems.

1. Introduction

The ability to use nature as a source of inspiration for developing the framework for technical innovations has been successful in many subjects related to materials science: hybrid materials,¹ adhesion,² self-healing materials,³ self-cleaning materials,⁴ or high strength fibers.⁵ However, for years researchers

have limited themselves to mimicking only the structural part of the living systems. Recently, biomimetic responsive systems have attracted a lot of attention, as they combine at the same time structural similarities with the living systems but also, to some extent, their adaptability in response to external stimuli.⁶ Nowadays, terms like “artificial muscles”,⁷ “smart biomimetic responsive surfaces”,^{4,8} “artificial swimmers”,⁹ and “artificial molecular motors”¹⁰ are frequently encountered in literature.

In particular, research on “artificial muscles” or “smart materials” is one of the most dynamic fields in material science. Smart materials that respond to external stimuli by a change in shape and/or size, called also actuators, have been

used to produce forces and displacements for micro-robots, micro-pumps, and sensors.¹¹

Polymers are among the best candidates for the development of smart or responsive materials, because of established advantageous properties such as high processability, relatively low weight density, easy fabrication and low manufacturing costs.⁷ Many actuators based on polymer systems have been reported, such as hydrogels,¹² conducting polymers,^{7b} dielectric elastomers,¹³ shape memory polymers,¹⁴ or liquid crystalline elastomers.^{15–18}

Liquid crystalline elastomers (LCEs) have been the subject of intense research for more than 20 years and the domain has been already reviewed.^{15–18} LCEs

^aSchool of Chemistry and Chemical Engineering, Southeast University, Nanjing, 211189, China

^bDepartment of Chemical Engineering, Laboratory for Advanced Materials, Tsinghua University, Beijing, 100084, China

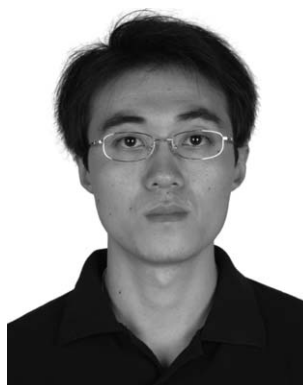
^cInstitut Curie, Centre de Recherche, CNRS UMR 168, Université Pierre et Marie Curie, 26 rue d'Ulm, 75248, Paris Cedex 05, France. E-mail: patrick.keller@curie.fr



Hong Yang

Hong Yang is an Associate Professor of Chemistry and Chemical Engineering at Southeast University. He earned his B.S. in Chemistry from Peking University in 2002, and his PhD in Chemistry from the University of Colorado at Boulder in 2007 with Prof. David M Walba. After one year of industry work as an associate director of medicinal chemistry in a Chinese pharmaceutical company, he went back to academia and joined Dr Patrick Keller's group

at the Institut Curie in 2008. Since completing his postdoctoral research, he joined the faculty at Southeast University in the spring of 2010. Currently, his research interests are liquid crystal materials and functional polymeric materials.



Gang Ye

Gang Ye is currently a lecturer in the Institute of Nuclear and New Energy Technology of Tsinghua University, Beijing, P. R. China. He received his PhD degree of polymer science from Tsinghua University in July 2010. The area of his research includes photo-responsive materials, soft-lithographical techniques, and optical sensors made of stimuli-responsive hydrogels.

combine the orientational ordering properties of liquid crystalline systems and the rubbery elasticity of polymer networks.¹⁵ Among others, their most interesting property is their ability to change reversibly their shapes and/or sizes under the application of external physical stimuli (temperature change, light, electric field, magnetic field, *etc.*).

In nematic LCEs, which are the object of this highlight, the actuation uses as the motor for the contraction/expansion cycle a reversible conformational change affecting the polymer chains at the molecular level. Before reaching the hearth of the highlight, we will briefly recall the actuation mechanism in nematic LCEs.

The basic idea behind the shape change in nematic LCEs was expressed 40 years ago by de Gennes: macromolecular chains dissolved in a nematic mesophase should adopt an anisotropic conformation because they will “feel” the anisotropic environment.¹⁹ de Gennes suggested to freeze the anisotropic conformation of the polymer chains by crosslinking them, the result being a conformationally anisotropic network swollen by the nematic mesophase. In a final step, de Gennes postulated that the removal of the nematic order around the anisotropic network would induce a conformational change of the macromolecular backbones from an anisotropic (oblate) shape to an isotropic (spherical) shape, and as a consequence, a change of shape of the whole network (Fig. 1).

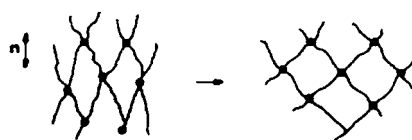


Fig. 1 Schematic representation of a polymer network in an oriented nematic mesophase. In the nematic mesophase (left), the network adopts an anisotropic conformation, elongated parallel to the nematic director. After removal of the nematic order (right), the network relaxes toward an isotropic conformation. Reproduced with permission from ref. 19.

Let us apply the scenario to a nematic LCE, in the present case a nematic main-chain LCE as an example. Consider long polymer chains with incorporated rod-like units (*i.e.* mesogens) within the chains, called main-chain liquid crystalline polymers (LCPs). As demonstrated by small angle neutron scattering experiments,²⁰ since the average macromolecular shape is coupled to the nematic orientational order, the polymer chains will elongate when their mesogens orient in the nematic phase, while, in the isotropic phase, they will recover a random coil conformation (Fig. 2a). A change in the average macromolecular shape, from elongated to spherical, is thus introduced as the nematic to isotropic phase transition takes place.

If these long polymer chains are now lightly cross-linked, a nematic main-chain LCE is obtained. If the nematic LCE is judiciously prepared, so that all the nematic polymer chains are, on average,

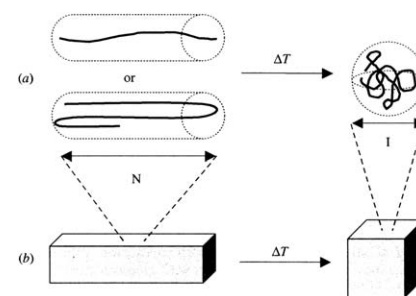


Fig. 2 (a) Conformation of a main-chain LCP in the nematic (N) and isotropic (I) phases. (b) Macroscopic shape change of a monodomain sample of a main-chain LCP at the nematic-isotropic transition.

oriented uniformly in the whole sample, the microscopic molecular level shape change will be translated to a collective, macroscopic shape change of the elastomer (Fig. 2b). The crosslinks will ensure a memory of the supramolecular organization present in the nematic phase; so, when the elastomer is cooled back below the nematic-isotropic transition temperature (TNI), the macroscopic sample will return to its initial shape.

Beside the thermomechanical effect described above, any physical stimulus, which can induce the nematic to isotropic phase transition, should work. Indeed, photomechanical effect has been described in azo-containing LCEs.^{17,21}

Following the pioneering work in Finkelmann's group,^{22,23} many nematic LCE “artificial muscles” have been described over the years.^{17,18,24} Until recently, all the systems described were of macroscopic



Xiaogong Wang

Xiaogong Wang is a full professor at Chemical Engineering Department of Tsinghua University, Beijing, P. R. China. He received his PhD degree of polymer science from Tsinghua University. He worked at Polymer Chemistry Department of Tokyo Institute of Technology (Japan) with Prof. Isao Ando as a visiting scholar from 1985 to 1986. He also worked at the Center for Advanced Materials, Chemistry Department of University of Massachusetts

Lowell (USA) with Prof. Sukant K. Tripathy as a postdoctoral fellow and visiting scientist from 1994 to 1997. His current research interests include functional polymers, polymer self-assembly and liquid crystal polymers.



Patrick Keller

Patrick Keller received his PhD in 1981 from the Université Paris Sud Orsay, working with Professor H. B. Kagan on solar energy. Since 1991, he has been a Director of Research with the French CNRS. His current interests focus on biomimetic materials, including artificial muscles made of liquid crystalline elastomers, stimuli-responsive surfaces and stimuli-responsive polymer vesicles.

size (hundreds of micrometres to several centimetres), mainly under the form of films^{17,18,24} or, in a limited number of cases, as fibers.^{25–28}

However, over the last few years, following a trend to miniaturization found in many fields of materials science, micron-sized LCE actuators have been described,^{29–39} with the aim to apply them in such domains like responsive surfaces (stimuli-induced roughness changes), microfluidic devices (micropump, microvalves, and microplugs) or microsensors. The preparations of these new micron-sized LCE actuators involve plenty of advanced techniques (soft lithography, microfluidic, microprinting, photomask technology, *etc.*), which have been developed previously for other applications in the latest two decades. Joining the mature LCE domain with these younger cutting-edge technologies has proved to be a very successful approach. In the present highlight, we will describe the most striking results obtained recently in the domain of micron-sized LCE-based responsive systems.

2. Micro-actuators: when artificial muscles made of nematic liquid crystal elastomers meet soft lithography

The generation of small structures is central to modern science and technology. Photolithography, as the key technology for microelectronic industry, and the most successful technology developed for microfabrication, is, however, an expensive and complex process, which is not easily accessible in regular laboratories. As an alternative, Whitesides and his team developed “soft lithography”,⁴⁰ a set of methods which have the common feature that they use a patterned elastomer as a stamp, mold or mask to provide access to 3D microstructures. The stamps, molds and masks were prepared by replica molding.

Replica molding starts by the duplication of micro- or nano-structured substrates (mother surfaces), using polymer materials such as PDMS elastomer, which will present the inverse geometry (daughter surface) of the one dimmed at (Fig. 3). In return, this PDMS duplicate will serve as a “stamp” or “mold” to prepare new microstructured surfaces,

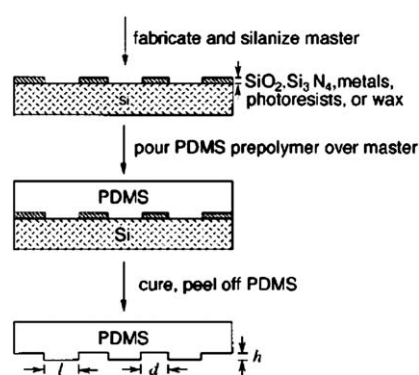


Fig. 3 Schematic illustration of the procedure for casting PDMS replicas from a master having relief structure on its surface. Reproduced with permission from ref. 40.

using techniques such as microprinting or replica molding. The mother surface or master can be any microstructured surfaces, either artificial such as the ones prepared by lithography^{40,41} or of natural origin such as the surface of lotus or rice leaves.^{42,43}

By applying the replica molding technique to the domain of nematic LCEs, we succeeded in preparing for the first time micron-sized LCE actuators, which behave as their macro-sized counterparts.^{29,35} Our goal was to prepare a microstructured surface such as the one presented in Fig. 4A: an array of nematic elastomer-made pillar actuators.

The setup we used is schematically presented in Fig. 4B. A PDMS elastomeric replica, consisting of an array of holes (size: 20 micrometres in diameter and 100 micrometres in depth), was prepared by replica molding and used as

a soft mold. Two key properties of this mold were exploited in this experiment: its transparency to UV light and its softness which facilitate the mold peel off.

As explained above, in order to obtain a macroscopic contraction resulting from the addition of the individual conformational change of the macromolecular backbones at a molecular level, polymer backbones had to be aligned parallel to each other and along the nematic director.²⁴ Referring to the term coined by Küpfer and Finkelmann,²² we had to create a nematic liquid single crystal elastomer in each pillar. Moreover, in order to obtain a fully reversible contraction–extension cycle, a memory of the macromolecular organization has to be introduced by crosslinking.²⁴ We used the same very simple approach we developed previously to prepare LCE actuator films: the simultaneous photopolymerization/photocrosslinking of an aligned nematic monomer/crosslinker/photoinitiator mixture.^{44,45} The only important difference was the replacement of the surface-induced alignment of the nematic director by a magnetic field induced orientation.⁴⁶ To achieve it, we used a readily available and chip NdFeB rare earth permanent magnet (Fig. 4B).

We first used a side-on nematic LC acrylate to prepare the pillar covered surface.²⁹ After UV irradiation and peeling off of the PDMS mold, a thin glassy polymer film covered by a regular array of pillars was obtained. To characterize their thermomechanical properties, pillars were cut off from the surface. When heated above the nematic to

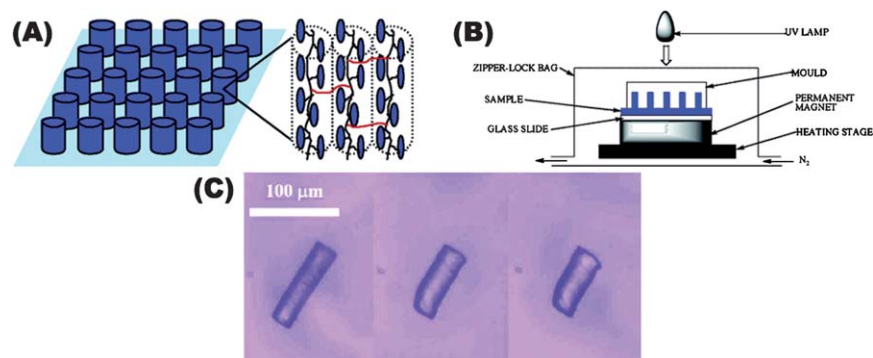


Fig. 4 (A) Schematic representation of an array of nematic elastomer-made pillars, showing the macromolecular organization in each pillar. (B) Experimental setup used to prepare the responsive micropillars. (C) An isolated micropillar heated (from left to right, the temperatures are 100, 120 and 130 °C) exhibits a reversible contraction along its major axis in the order of 35%. Reproduced with permission from ref. 29.

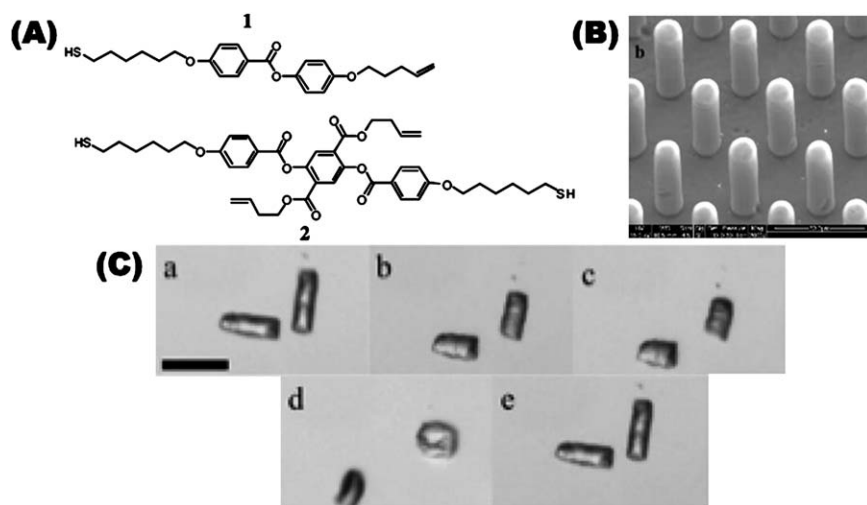


Fig. 5 (A) The new nematic thiol-ene monomer and tetrafunctional nematic crosslinker used to prepare main-chain LCEs. (B) SEM image of a surface covered with large cylindrical pillars. (C) Contraction of isolated nematic main-chain LCE micropillars heated up to the isotropic (a–d), then cooled back to room temperature (e). Scale bar is 100 μm . Reproduced with permission from ref. 35.

isotropic transition temperature, the monodisperse cylinders underwent a reversible contraction of around 35 to 40% (Fig. 4C). Those micro-pillars were the first published example of micron-sized nematic LCE actuators. However, the use of nematic side-on LCEs was clearly a limiting factor in the small contraction we observed. As explained previously,²⁴ and observed experimentally,^{23,26} nematic main-chain LCEs are the materials with the highest contractions reported on films or fibers, around 400 to 500%. However, all the main-chain LCEs described so far are prepared using the two step crosslinking procedure under mechanical stress, as originally described by Finkelmann *et al.*²¹ The choice is very limited for a photochemically induced polycondensation approach to the synthesis of main-chain LCP.^{47–50} The photoinduced addition of thiols on olefins (the so-called thiol-ene photopolymerization) is a well-known click reaction, resulting in linear polymers.⁴⁷ Following the pioneering work of Lub *et al.* on the photopolymerization of thiol-ene monomers,^{47,48} we prepared a new nematic thiol-ene monomer and a new tetrafunctional nematic crosslinker (Fig. 5A). Using the same setup described previously (Fig. 4B), we obtained thin glassy polymer films covered by pillars of different shapes and sizes, as explored by environmental scanning electron microscopy (Fig. 5B). Those pillars, when heated

above their nematic to isotropic transition temperature, contract reversibly of around 300 to 400% (Fig. 5C).

The nematic main-chain LCE microactuators described here present contractions as large as the best macroscopic systems reported in the literature.^{23,26} The straightforward method used to prepare LCE microactuators with ultralarge contraction paves the way for the development of LCE-based responsive surfaces

mimicking natural surfaces with specific properties. This procedure could be easily extended to the preparation of nematic azo main-chain LCE microactuators with photomechanical properties, similar to the ones described for macroscopic systems.^{17,21,45}

3. A continuous flow synthesis of micrometre-sized actuators from LCEs in a microfluidic setup

Microfluidic devices have been recently developed for the synthesis of polymer particles with sizes in the range of a few to several hundred micrometres. Depending on the experimental conditions, the polymerization of monomer emulsions can produce polymer particles with various shapes: spheres, disks, rods, and janus.⁵¹ In an oversimplified presentation of the principle, the monodisperse droplets of a liquid monomer are generated by injecting this monomer into a co-flowing stream of an immiscible liquid *via* a thin needle (Fig. 6). Then, the formed monomer emulsion flows through a piece of thin tubing under the illumination of a UV lamp, which induces the photopolymerization of the monomers to give the polymer particles. The particles are recovered after separation from the immiscible inert fluid by sedimentation.

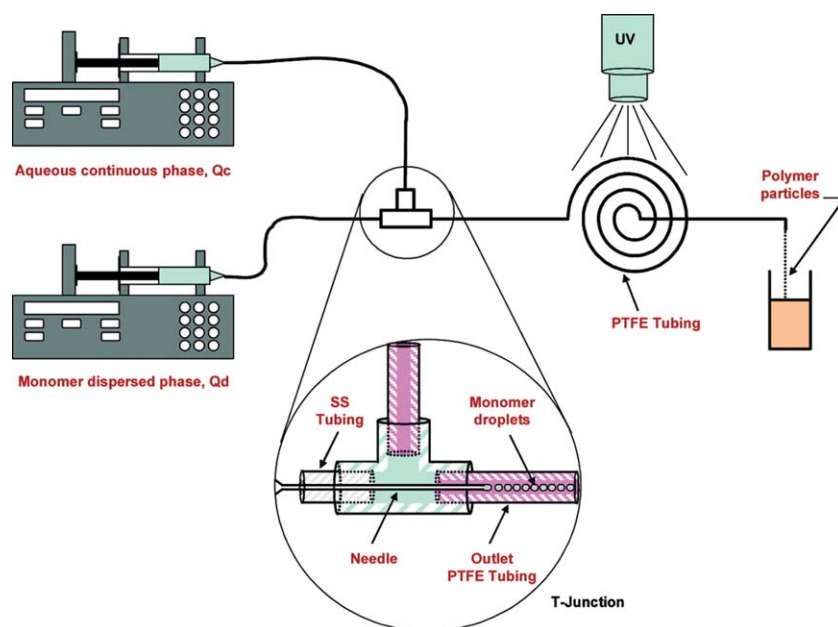


Fig. 6 Schematic presentation of the microfluidic system for the synthesis of controlled size polymer particles. Reproduced with permission from ref. 51.

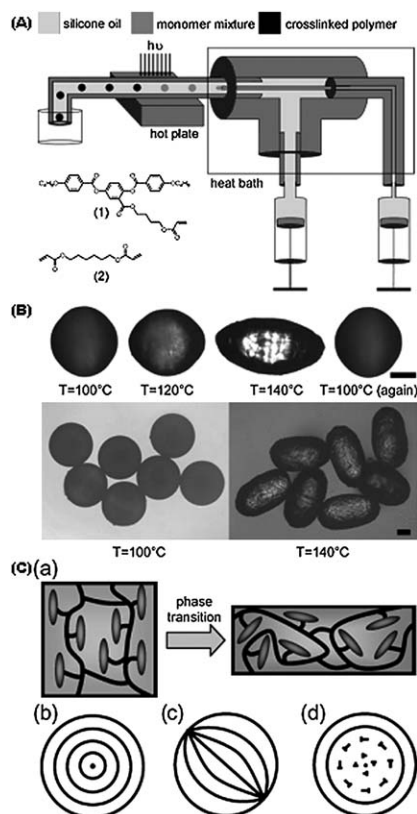


Fig. 7 (A) Schematic drawing of the microfluidic setup and the chemical structures of the LC monomer and crosslinker used in the experiment. (B) Microscopy images of heating experiments with crosslinked LC particles. The upper row shows a particle at different temperatures. It reversibly changes its shape from spherical to elongated. The lower row shows a collection of particles in the nematic (100 °C) and in the isotropic (140 °C) phases. They all deform in the same way. (C) In (a), a schematic illustration for the mechanism of the deformation of a LCE particle is presented. The 3 bottom images show possible director field orientations in a spherical nematic particle: concentric (b), bipolar (c) and escaped concentric (d).

In order to adapt this technique to the synthesis of micrometre-sized LCE particles, Ohm *et al.* had to realize a technical “tour-de-force”.^{36,37} All the process starts by the injection of a liquid monomer in an immiscible fluid *via* a small needle. However, all known nematic LC monomers are solid at room temperature. So, the whole setup had to be temperature-controlled in order to work with the LC monomer in its isotropic liquid form (Fig. 7A). After their formation, the isotropic monomer droplets moved downstream and cooled in their nematic

mesophases, then passed through a piece of thin tubing exposed to a UV lamp where the photopolymerization/photocrosslinking took place. This method allows the production of large amounts of monodisperse particles, like the ones shown in Fig. 7B. The sizes of the droplets prepared by the method of co-flowing injection can be efficiently controlled by tuning the ratio between the flow rates of the continuous isotropic liquid and dispersed LC monomer phase. Particles with diameters ranging from 250 to 550 micrometres were obtained. Those spherical LCE particles, when heated from room temperature to the isotropic phase (around 130 °C), deformed reversibly to adopt an elongated ellipsoidal shape (Fig. 7B). As shown in the figure, a collection of particles all behave in the same way. Thus the LCE particles are real micrometre-sized actuators with length changes of about 70%.

As demonstrated in Fig. 7B, the reversible deformation is related to the nematic to isotropic phase transition of the LCE. Thus, this shape change should be related to a conformation change of the polymer backbone, as described previously for the LCE micropillars.^{29,35} However, the macroscopic contraction, to be observed, needs to take place in a nematic LCE monodomain.²² Authors propose that the mesogens adopt a uniform concentric alignment in the spherical particles^{36,37} (Fig. 7C), induced by the flowing motion during the travel-

ing along the setup and frozen by the photopolymerization/photocrosslinking process.

Among others, the main advantage of the microfluidic approach toward the preparation of micrometre-sized LCE actuators is the possibility of mass production of the objects with controlled size, adjustable deformation, *etc.* The discovery of a room temperature nematic side-on LC monomer would tremendously increase the practical usefulness of the technique. Moreover, as stated previously for the LCE micropillars, it could be very interesting to extend the present work to the preparation of azo-containing systems with photomechanical properties.

4. Photopatterned liquid crystalline polymers for microactuators

In the continuous developments of microelectromechanical systems (MEMS), polymers are seen as very promising materials. Patternability is an important requirement for materials being considered for application in MEMS. Some years ago, Broer *et al.* demonstrated that LCPs can be patterned using a single-step mask exposure during photopolymerization.⁵² During this process, the liquid crystalline organization was preserved. Elias *et al.* proposed to use photopatterning to prepare surface-covered LCE microactuators.^{31–33}

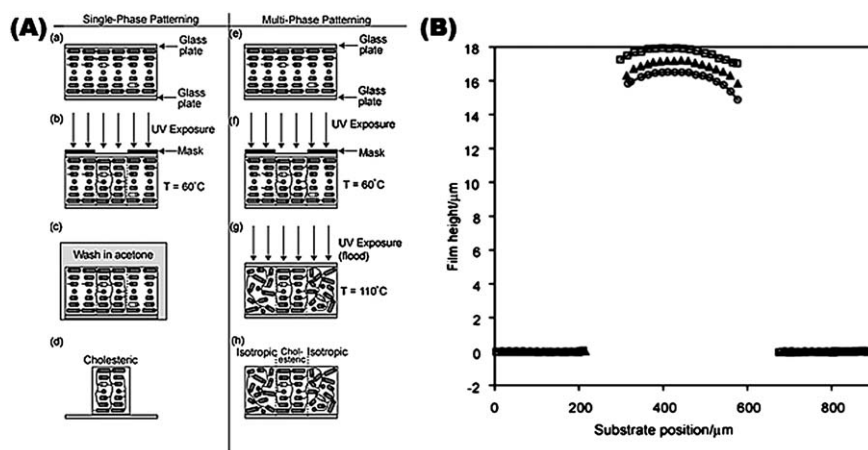


Fig. 8 (A) Process flow diagram for photopatterned LC polymer films. Single phase patterning to give a structured cholesteric film on a bare substrate (a to d). Multi-phase patterning to give a solid film comprised of isotropic and cholesteric domains (e to h). (B) Surface profile of a single-phase patterned substrate. As the sample is cooled from 200 to 25 °C, the height of the photopatterned relief structure decreases by 8.4% and the process is reversible. Reproduced with permission from ref. 31.

Photopatterning can be performed in two different ways as presented in Fig. 8A. In the single-phase patterning, the LC monomer mixture is photopolymerized by irradiating through a mask. In a second step, unexposed material is washed out to leave the photopatterned microstructure standing on the bare substrate (Fig. 8A, a–d). In the multi-phase patterning, after the initial photopolymerization through the mask, the sample is heated to the isotropic phase of the liquid crystalline monomer mixture, and then the whole sample is UV-irradiated, resulting in a thin heterogeneous film, comprising LCE microdomains embedded in an isotropic matrix (Fig. 8A, e to h). The two areas will exhibit different thermo-mechanical responses.

In their study, authors used a mixture of a side-chain monoacrylate as the nematic monomer and a mesogenic diacrylate as the crosslinking agent. To get a cholesteric mesophase, a chiral agent (BASF LC756) was added. The surfaces of the cell were coated with polyimide and rubbed to induce a planar alignment. Actuation of the patterned cholesteric structures was observed using interferometry.

Samples obtained by multi-phase photopatterning exhibited very modest actuation properties, around 1.6%. Samples obtained using single-phase patterning presented much more interesting reversible deformations, up to 8.4% (Fig. 8B). The deformation is not related to any sudden phase transition but is rather a continuous process. Moreover, in opposition to what was described previously for the micropillar actuators, the patterned structure thickness decreases when temperature is decreased. Although authors did not elaborate in the paper on the mechanism responsible for the observed actuation, we can safely assume that it is the same mechanism proposed by Crawford *et al.* in a previous paper³² for a densely crosslinked LC network: “the thermal expansion of the reactive mesogens is substantially lower along the long molecular axis than normal to it, owing to the fact that most of the covalent bonds that make up the polymer network are parallel to the long axis of the molecules”.

Although the amplitude of the contraction–extension remained relatively

modest, this paper demonstrated that a lithographic exposure through a mask enabled the formation of micrometre-sized actuators that could be integrated into microelectromechanical system devices.

5. Printing of monolithic polymeric microstructures using reactive mesogens

As pointed out previously, over the last decade, soft lithography has been developed as an alternative to classical “hard” lithography to prepare 3D microstructures. The soft patterned elastomers produced by this technique can be used as molds as presented previously. They can also be used as stamps in conjunction with “inks” to prepare microstructured surfaces. The different steps of micro-contact printing (μ CP) process are summarized in Fig. 9A.

The “ink” used can be of various nature: polymer solution, bio-macromolecules, liquid crystal, *etc.*⁵³ In their experiments,³⁴ Sanchez *et al.* used as a nematic ink a commercial diacrylate (RM 257 Merck) with a high temperature nematic mesophase. The inking and printing steps had to be done at elevated temperature in order to use this nematic

ink. The stamps consisted in an array of square-topped pyramids with a lateral dimension of 140 micrometres. The reactive mesogen was printed on a rubbed polyimide covered surface to induce a planar alignment of the nematic mesophase. After photopolymerization, polarizing optical microscope images of the patterned surface demonstrated clearly the success of the approach (Fig. 9B). Optical profilometer images gave an accurate characterization of the height of the printed squares, around 2 micrometres. As authors developed the printing techniques with optical

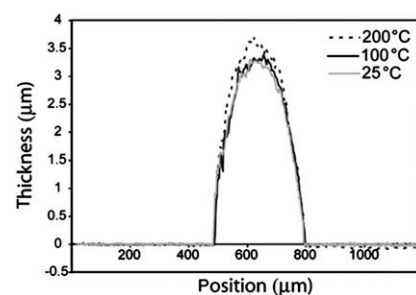


Fig. 10 Thermal actuation of a microtransfer printed structure. The overall thickness of the structure decreases by 9% as the temperature is decreased from 200 to 25 °C. Reproduced with permission from ref. 33.

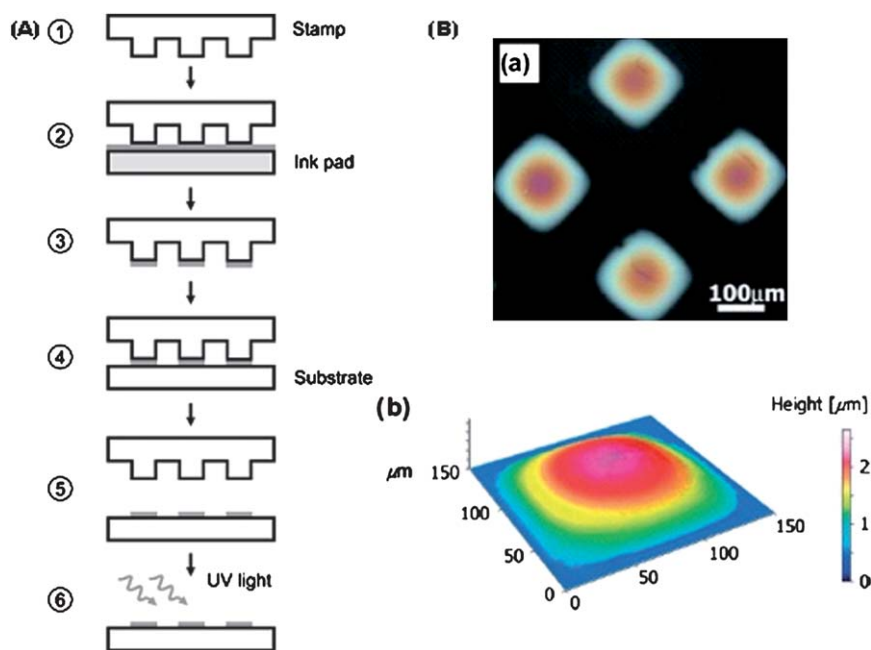


Fig. 9 (A) Schematic representation of the printing process for a photocurable ink. (B) (a) Polarisation optical microscope image of a pattern of squares printed on a rubbed polyimide using a reactive LC. (b) Optical profilometer image of a single printed square. Reproduced with permission from ref. 34.

applications in mind, they did not study the thermal properties of the individual microstructures. However, using the same mixture of compounds used in ref. 31, Elias *et al.*³³ described the thermal actuation of a microtransfer printed structure, although of larger size (a few hundred of micrometres). The overall thickness of the structure decreased by around 9% as the temperature decreased from 200 °C to room temperature (Fig. 10). As for the photopatterned microactuators describes before,³¹ the anisotropic thermal expansion of the microstructure is at the root of the observed thermomechanical effect.

The microtransfer printing technique is an attractive approach for the preparation of microactuators over large surfaces. As compared with the photopatterning, its main drawback could be a difficulty in controlling the height of the microstructures.

6. Printed artificial cilia from liquid crystal network microactuators modularly driven by light

The ability to pattern surfaces with functional polymers has contributed strongly to the development of various research domains such as tissue engineering, biosensors, and plastic electronics.⁵⁴ Several patterning methods have been used over the years, including photolithography, soft lithography, micro-contact printing or direct writing techniques (scanning probe microscope lithography, dip-pen nanolithography or inkjet printing). In inkjet printing, a polymer or monomer solution breaks up

into droplets, which are deposited onto a surface according to a predefined pattern (Fig. 11).

van Oosten *et al.* used reactive liquid crystal monomer inks and an inkjet printer to produce microactuators under the form of artificial cilia.³⁸ In order to remotely control the movements of the artificial cilia, authors chose to use the photomechanical effect already developed using azo LCEs.^{21,17,24} They also used the self-assembling properties of nematic liquid crystal and the possibility to orient the director using surface or surfactant effects, to build thin films with a splay-bend molecular organization through the thickness of the film (Fig. 12A).

The inks are complex mixtures of mesogenic monomers and crosslinkers dissolved in a solvent, and doped with two different azo dyes, A3MA or DR1A

(Fig. 12B). Since those azo dyes have different absorption spectra, it is in principle possible to induce photomechanical responses for two different light wavelengths, UV and visible. To manufacture freestanding microactuators, four basic processing steps were implemented (Fig. 12C). At first, a sacrificial layer of polyvinyl alcohol was deposited on a glass surface, followed by a thin layer of rubbed polyimide alignment layer, which will induce a homeotropic alignment of the nematic compounds (Fig. 12C, b). Then, the first mixture of monomers/crosslinkers/azo dye dissolved in an appropriate solvent is deposited using a commercial inkjet printer and photopolymerized to give the first part of the LCE-made cilia. The same deposition procedure is conducted again using another mixture, producing the second part of the cilia (alternatively, cilia made

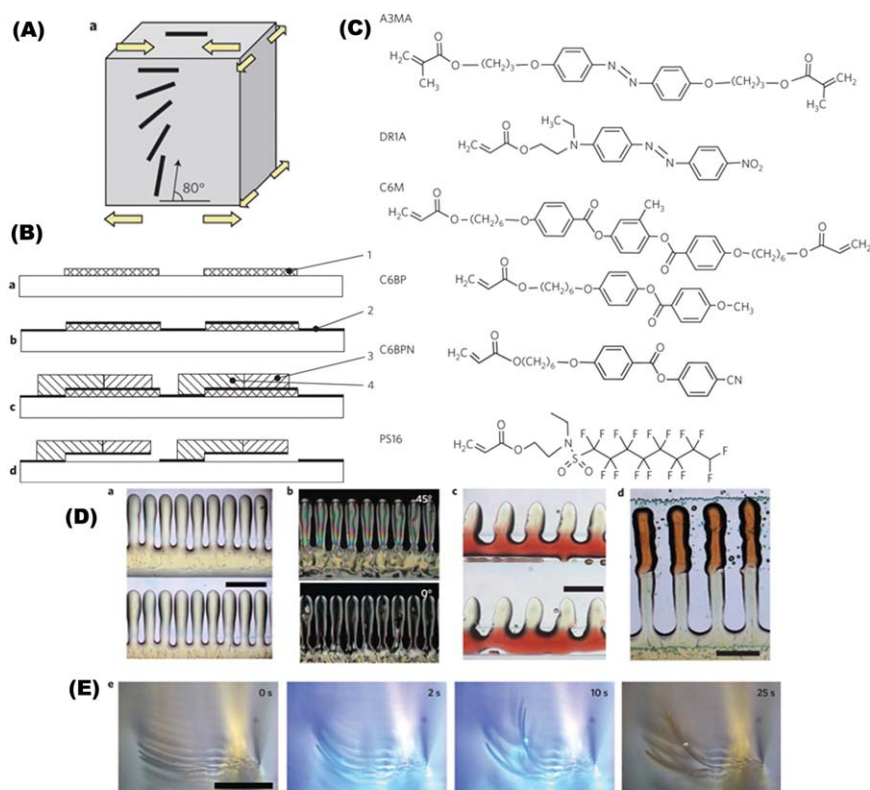


Fig. 12 (A) Schematic representation of a splay-bend molecular orientation through the thickness of the film. The arrows indicate the direction of the material response on actuation. (B) The monomers, crosslinkers and azo dyes used in the preparation of the photo-actuated artificial cilia. (C) The four basic processing steps to produce the artificial cilia. (a) Structured deposition of the PVA release layer (1). (b) Spin coating, curing and buffing of the polyimide alignment layer (2). (c) Inkjet deposition of the monomer mixtures containing DR1A (3) and A3MA (4) and curing. (d) Dissolving the PVA release layer. (D) Microstructured cilia: (a and b) arrays of A3MA cilia. (c) Cilia manufactured with a gradient in composition from DR1A to A3MA polymer. (d) Cilia made with two separate parts of DR1A and A3MA polymers. (E) Side view of the actuation of A3MA cilia with UV light in water. Reproduced with permission from ref. 38.

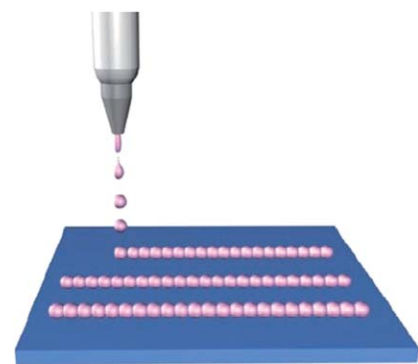


Fig. 11 Inkjet printing: schematic of the patterning process. Reproduced with permission from ref. 54.

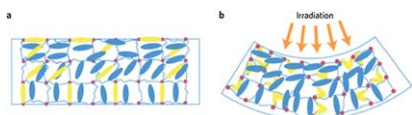


Fig. 13 Mechanism of light-induced bending in photoresponsive cilia. (a) Mesogenic units (blue) and azo crosslinker (yellow) in the *trans*-state align parallel. (b) Upon UV irradiation, the azo crosslinkers undergo *trans*–*cis* isomerization, contracting the network in the horizontal direction on top, and dilating it on the bottom, causing bend. Reproduced with permission from ref. 39.

of only one LCE material can be made) (Fig. 12C, c). In the last step, the whole setup is plunged in water to dissolve the sacrificial PVA layer, releasing the cilia (Fig. 12C, d). In Fig. 12D, representative examples of microstructured cilia are presented. Cilia made of an LCE doped with A3MA, when irradiated with UV light from above, bends upward, the bending radius being dependent on the light intensity (Fig. 12E).

As schematized in Fig. 13,³⁹ the mechanism of the light-induced bending in the artificial cilia is related to the *trans*–*cis* isomerization of the azo groups. The *trans*-, rod-like, state of the molecules aligns with the nematic host, whereas the bent *cis*-state decreases the order of the nematic host, inducing a macroscopic shape change of the material.

Behind the realization of these light-driven artificial cilia made of LCEs, which, in itself, is a real technical prowess, authors propose applications and in particular the pumping and mixing in microfluidic systems. The cilia for these applications are made of two distinct and separately addressable parts with different bending properties. As pointed out by Palfy-Muhoray,³⁹ activating these two parts in sequence using two different light wavelengths will imply the motion of the cilia is non-reciprocal, and the cilia will be able to pump fluids.

With this new developed system, which makes use of relatively simple inkjet printing technique, LCE-based micro-actuators are making a huge step toward real, useful applications.

7. Concluding remarks

The generation of small structures is central to modern science and technology. Responsive micron-sized systems, which

can adapt to surrounding environment, are playing an increasingly important part in a diverse range of applications, such as drug delivery, microelectromechanical systems, biosensors or smart surfaces. Micron-sized liquid crystalline elastomers are gaining a lot of attention recently, since they are easy to prepare using various low-cost techniques (replica molding, microfluidic or inkjet printing). Their mechanical properties can be conveniently modulated, from high strain–low stress materials for weakly crosslinked LCEs, to low strain–high stress materials for highly crosslinked LCEs.

In this highlight, we have presented the most promising results obtained in the preparation of micron-sized LCE actuators. However, so far most of them have not been engaged in “real applications”, but we are confident that in the near future this problem will be successfully solved by a new generation of researchers coming from all over the world.

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