

# Directed bending of a polymer film by light

Miniaturizing a simple photomechanical system could expand its range of applications.

Polymer solutions and solids that contain light-sensitive molecules can undergo photo-contraction, whereby light energy is converted into mechanical energy<sup>1–8</sup>. Here we show that a single film of a liquid-crystal network containing an azobenzene chromophore can be repeatedly and precisely bent along any chosen direction by using linearly polarized light. This striking photomechanical effect results from a photoselective volume contraction and may be useful in the development of high-speed actuators for microscale or nanoscale applications, for example in micro-robots in medicine or optical microw tweezers.

We prepared the films by thermal polymerization of a liquid-crystal monomer (molecule **1** in Fig. 1a) and a diacrylate crosslinker (molecule **2**) (9:1, mol/mol), both of which possess azobenzene moieties. Figure 1b shows a sequence of frames indicating how such a film can be bent along a precisely controlled direction by irradiation with linearly polarized light (for movies, see supplementary information).

The first frame in Fig. 1b shows the film before light irradiation; counting clockwise, the second shows how the film curls up after exposure to 366-nm light that has a polarization direction at zero degrees. The film is bent towards the direction of irradiation of the light, with the bending occurring parallel to the direction of light polarization (Fig. 1b, white arrows). When the bent film was exposed to visible light with a wavelength longer than 540 nm, it completely reverted to its initial flat state (third frame in Fig. 1b).

The effects on the film of altering the polarization direction of light at 366 nm to  $-45^\circ$ ,  $-90^\circ$  and  $-135^\circ$  are shown in the fourth, sixth and eighth frames, respectively, of Fig. 1b. It can be seen that the bending direction of the film moves anticlockwise by  $45^\circ$ ,  $90^\circ$  and  $135^\circ$ , respectively, keeping parallel to the direction of light polarization. The film could be restored from each bent state to its initial flat form by irradiation with visible light at wavelengths longer than 540 nm (Fig. 1b). Moreover, the bending–unbending cycle of these four modes could be repeated without apparent fatigue. These results show that the bending direction of a single film can be precisely controlled by altering the direction of polarization of the irradiating light, and that such a film can be bent repeatedly.

In the film used here, the incident light is mostly absorbed by the film surface because of the strong absorption by the azobenzene moieties of light at about 360 nm. The film is a polydomain liquid-crystal film that consists of many micro-sized domains of

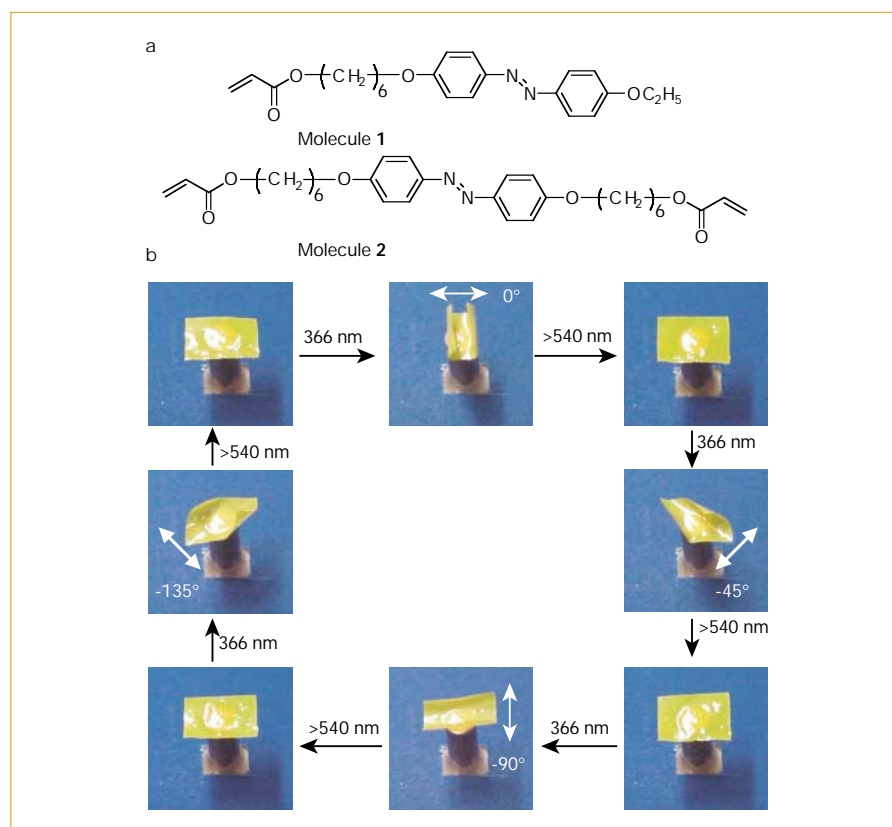
azobenzene liquid-crystal moieties aligned in one direction in each domain, although macroscopically the direction of alignment is random. On irradiation of the film with linearly polarized light, the selective absorption of light of a specific direction leads to a *trans*–*cis* isomerization of the azobenzene moieties in specific domains where the azobenzene moieties are aligned along the direction of light polarization.

As a result, the subtle reduction in microscopic size and ordering of the liquid-crystal components<sup>1–4,9,10</sup> gives rise to a substantial macroscopic volume contraction<sup>5–8</sup> at the film surface and a bending of the whole film as a result of the cooperative movement of the liquid-crystal moieties and polymer segments. Light energy is therefore efficiently converted into mechanical energy. It should be simple to miniaturize our system for potential application in driving micro-machines and nanomachines without the

aid of batteries, motors and gears, using remote irradiation with laser beams.

**Yanlei Yu, Makoto Nakano, Tomiki Ikeda**  
*Chemical Resources Laboratory, Tokyo Institute of Technology, 4259 Nagatsuta, Midori-ku, Yokohama 226-8503, Japan*  
 e-mail: [tikeda@res.titech.ac.jp](mailto:tikeda@res.titech.ac.jp)

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**Figure 1** Precise control of the bending direction of a film by linearly polarized light. **a**, Chemical structures of the liquid-crystal monomer (molecule **1**) and crosslinker (molecule **2**) used for preparation of the film. On cooling from  $95^\circ\text{C}$ , **1** changes from an isotropic to a nematic phase, and at  $91^\circ\text{C}$  it becomes crystalline; molecule **2** undergoes a phase transition from crystalline to isotropic at  $98^\circ\text{C}$ . **b**, Photographic frames of the film bending in different directions in response to irradiation by linearly polarized light of different angles of polarization (white arrows) at 366 nm, and being flattened again by visible light longer than 540 nm. The flat film ( $4.5\text{ mm} \times 3\text{ mm} \times 7\ \mu\text{m}$ ) lay on a copper stick fixed to a copper plate; a stage under the plate was set at  $85^\circ\text{C}$  to control the temperature of the film, which was covered by a piece of blue paper. The bending time for the four different bending directions was within 10 s, when the light intensity of 366-nm linearly polarized light was  $3.5\text{ mW cm}^{-2}$  after exposure to visible light longer than 540 nm ( $547\text{ nm}$ ,  $24.2\text{ mW cm}^{-2}$ ;  $577\text{ nm}$ ,  $26.8\text{ mW cm}^{-2}$ ), the bent film reverted to the flat state in about 10 s.