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RAPID COMMUNICATION

Photodeformable polymer material: towards light-driven micropump applications

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Abstract The deformation of a photodeformable film material is studied based as regards the constitutive relations. In the theoretical analysis, a model for the deflection of the laminated sample upon the irradiation of ultraviolet (UV) light is established and the bending moment is deduced. Furthermore, the deflection of the film can be calculated using finite-element analysis (FEA) software. Then the attempt to utilize the superior characteristics including shape memory and large internal force on the application of a micropump is undertaken in our study. The force produced in the reciprocating deformation of the film sample is of potential to activate the pump membrane. A set of experimental devices are designed to test the performance of the membrane in the experiment. The flow volume in a stroke is close to simulation result obtained by FEA.

1 Introduction

A kind of photodeformable crosslinked liquid-crystalline (LC) polymer film, which could bend upon the irradiation of UV light and revert to its initial flat state upon visible light, has attracted considerable attention from the material-research community in recent years [1]. Photochromic molecules such as azobenzenes can undergo a reversible photochemical reaction between two forms [2]. Therefore, when azobenzenes are incorporated into LC molecules, the mixtures can also show a photochemical phase transition which is reversible. LC polymers containing azobenzene moieties show contraction along the alignment directions of mesogens and thus deformation can be induced upon the irradiation of UV light.

This kind of photoinduced reversible deformation is different from that caused by chemicals, because it does not need contact or exchange of chemicals, but just non-contact energy to realize the control of its shape. Compared to magnetostrictive, piezoelectric or heatresponsive materials, photodeformable material would be widely applicable because they can be controlled remotely just by manipulating the irradiation conditions. Furthermore, light is a superior energy source, which can be controlled instantly and precisely [3]. Therefore, this photodeformable material is viewed to have great potential to be used in MEMS applications. Ikeda et al. [3] developed a plastic motor driven only by light with LCE films and their composite materials. They also realized various three-dimensional movements of LCE films, such as the movement of inchworm and robotic arm [4].

Since its invention in 1970, almost the whole range of microactuation techniques have been applied for the design of a micropump [5], including piezoelectric, thermopneumatic, electrostatic and electromagnetic actuation. Laser is also brought in as a kind of microactuation method. In the design of Shoji Maruo [6], the micropump can be driven by means of radiation pressure generated by focusing a laser beam. However, UV light and visible light are more available resources and cost less to be utilized. And in regard to the periodical bending behavior and large deformation of the photodeformable laminated film, this material has great potential in the application of microfluidics.

In our study, the bending behavior of the LC polymer film is utilized to activate the movement of pump membrane. The

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mechanics model is established to analyze the deformation of the membrane upon the irradiation of UV light. A set of experimental devices are designed to test the deflection of the membrane in the experiment.

2 Theoretical analysis

2.1 Materials

The materials used in this study have been developed by the lab of Prof. Yanlei Yu in Fudan University, and the chemical structures of compounds used in this study are shown in Fig. 1. It is a mixture of DA11AB/A9BZ9/C9A = 20/40/40 (mol%) [7].

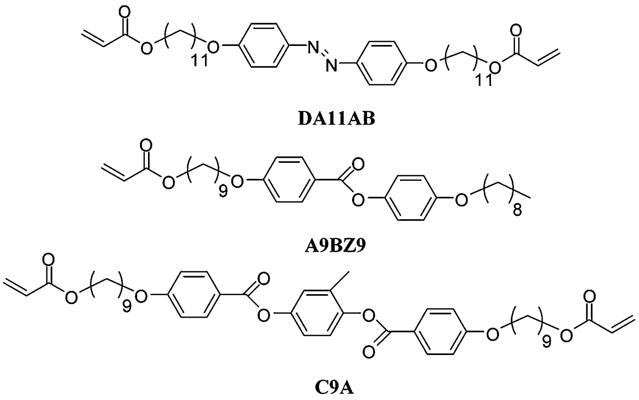


Fig. 1 Chemical structures of compounds used in this study

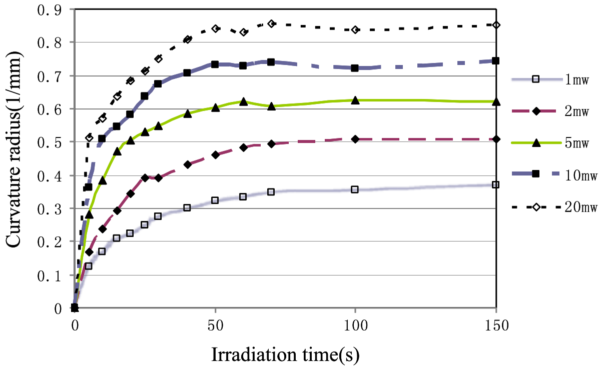


Fig. 2 Curvature radius measurement upon irradiation of UV light

To evaluate the bending capability of the laminated film of this material by irradiation, we measured the curvature radius of the films upon exposure to UV light. The bending speed is strongly dependent on the optical intensity, as shown in Fig. 2. The higher the intensity, the faster the film bends and the larger the curvature radius.

2.2 Model of the photoinduced stress-strain analysis

To analyze the photomechanical behavior of the film applied as the driving source, as shown in Fig. 3, select a micro element p from the laminated model of the film to build our discussion. Considering the thickness is so small compared to the size in the other two directions, according to Kirchoff hypothesis, $\gamma_{xz} = \gamma_{yz} = \varepsilon_z = 0$. Under small deflection conditions, the strain of the photodeformable material upon the irradiation of UV light consists of two parts, the photostrain induced by irradiation and the elastic strain induced by contraction [8], i.e.

$$\varepsilon^e = \varepsilon - \varepsilon^m = \left\{ \begin{array}{c} \frac{\partial u}{\partial x} \\ \frac{\partial v}{\partial y} \\ \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \end{array} \right\} - \left\{ \begin{array}{c} \varepsilon^m(I) \\ -\frac{1}{2}\varepsilon^m(I) \\ 0 \end{array} \right\} \tag{1}$$

The corresponding stress can be expressed as

$$\sigma = Q\varepsilon^e = Q\left(\varepsilon - \varepsilon^m\right) = Q\varepsilon - Q\varepsilon^m \tag{2}$$

Where Q is a symmetric 3×3 matrix of elastic constants [9], that is,

$$Q = \begin{bmatrix} 4/3 & 2/3 & \\ 2/3 & 4/3 & \\ & & 1/3 \end{bmatrix} E \tag{3}$$

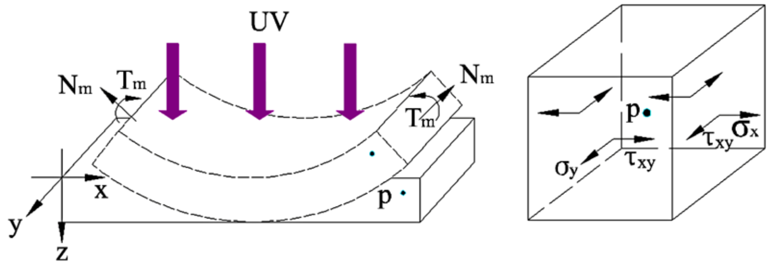
$$\sigma^m = Q\varepsilon^m = \left[E\varepsilon^m(I) \quad 0 \quad 0 \right] \tag{4}$$

Similar to Duhamel Similarity Theorem in thermodynamic theories, the photomechanical effect can be converted into the stress σ^m distributed on the x–y plane.

The light intensity decays exponentially through the thickness of the film due to the photon absorptions, that is [8]

$$I(z) = I_0 \exp\left(-\frac{z}{d}\right) \tag{5}$$

Fig. 3 Photodeformable laminated model



where z is the distance to the surface, I_0 is the optical intensity on the surface and the positive constant d is the decay distance induced by the photon absorption. Therefore, the photoinduced stress σ_x^m varies through the thickness, that is, σ_x^m is dependent on z. Integrate σ_x^m into the axial force N^m in the x direction and the bending moment T^m in x–z plane, which causes the beam to bend:

$$N^m = b\int_0^h \sigma_x^m(z)\,dz = Eb\int_0^h \varepsilon^m(I_z)\,d_z \tag{6}$$

$$T^m = Eb\int_0^h \varepsilon^m(I_z)\left(z-\frac{h}{2}\right)dz \tag{7}$$

With regard to the photostrain for the film sample used in our research, it can be expressed as follows,

$$\varepsilon_m(I_z) = \frac{K\tau_{ct}\eta I_z}{1+\tau_{ct}\eta I_z} = \frac{K\tau_{ct}\eta I_0 e^{-\frac{y}{d}}}{1+\tau_{ct}\eta I_0 e^{-\frac{y}{d}}} \tag{8}$$

where $K = 0.11$, $\tau_{ct} = 50$, $\eta = 0.15$, $d = 0.0001$, as measured in the experiments.

2.3 Application as micropump membrane

Supposing that we apply the forces produced in deflection of the film sample to a membrane which covers on a sealed space, as shown in Fig. 4. The photodeformable material can show periodical bending and unbending on the irradiation of UV light and visible light, thus the membrane shows periodical reciprocating movement at the stimulation of the deformation of the material. Therefore, the characteristic of this material has potential to be applied on micropump. On the irradiation of UV light, the distinction of the contraction ratio through the thickness gives rise to the downward bending of the film resulting in the reduction of the pump chamber volume. Therefore, overpressure is generated in the pump chamber and fluid flows into the outlet pipe. On the irradiation of visible light, the upward unbending of the film leads to the expansion of the pump chamber. Underpressure in the chamber drives the fluid to flow through the inlet valve into the chamber. The repeating cycle can realize the one-way activation of the liquid.

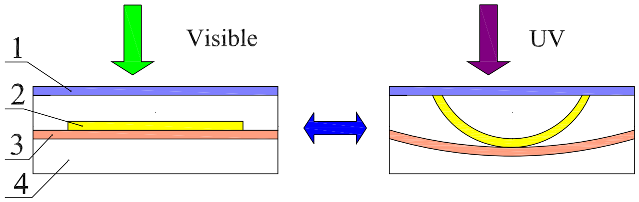


Fig. 4 Exert the photodeformable film on pump membrane (1 press plate, 2 photodeformable film, 3 pump membrane, 4 pump chamber)

Based on the discussions above, we calculate the deflection of the pump membrane in FEA software, as shown in Fig. 5. The optical intensity in calculation is 150 mW/cm^2, which is the parameter in the following experiments. The maximum deflection in the middle of the membrane is 0.54 mm.

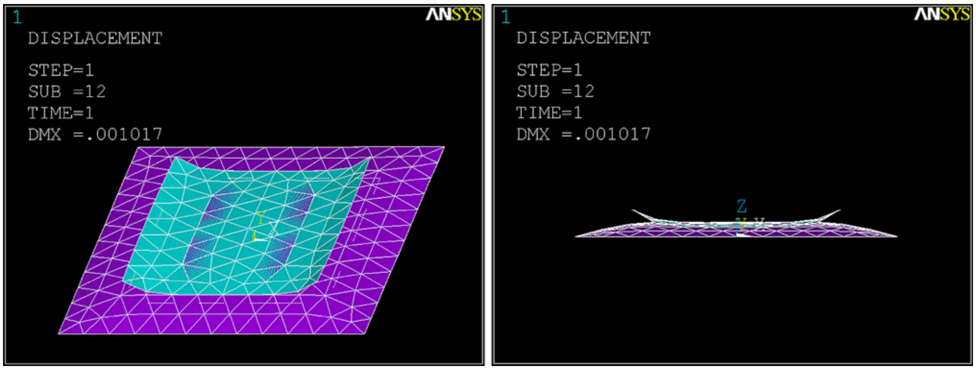
Considering the shape of the deflected membrane is similar to cone, therefore the volume generated in a stroke can be calculated as follows:

$$\begin{aligned} V &= \frac{1}{3}\pi R^2\Delta h = \frac{1}{3}\pi \times (0.005)^2 \times 0.54 \times 10^{-3}\ \mathrm{m}^3 \\ &= 14.1\ \mu\mathrm{l} \end{aligned} \tag{9}$$

3 Experiment

Here we designed a model of photo-activated micropump with the membrane driven by the photodeformable film, to explore the possibility of the application on micropump. The structure of the photo-activated micropump experimental prototype is shown in Fig. 6. It mainly includes photodeformable material, pump membrane, pump chamber, and pipes. The plates which formed the pump are made of polymethylmethacrylate (PMMA). The PMMA parts are fabricated with conventional cutting and milling techniques. Water is chosen as the pump medium. The investigated pump

Fig. 5 The deformation of the pump membrane shown in Ansys



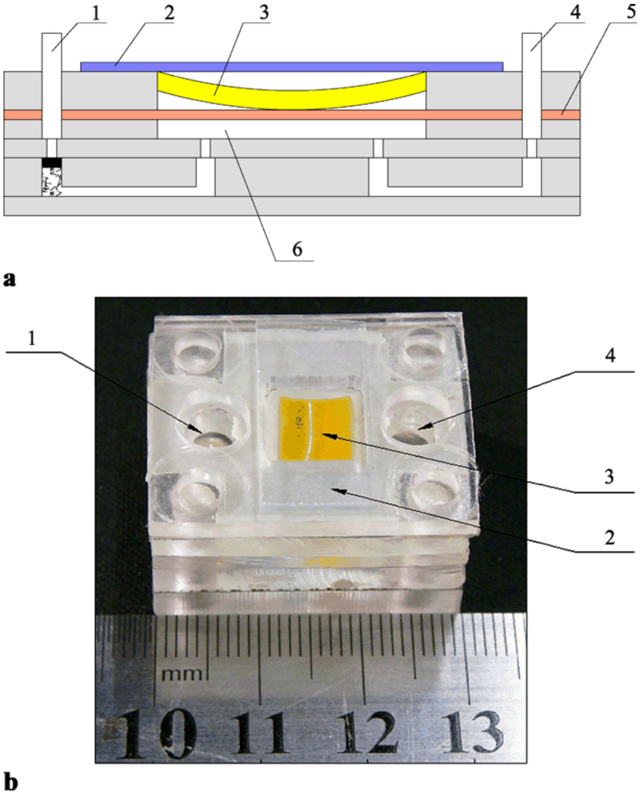


Fig. 6 **a** The section of the assembled prototype. **b** Photo of the experimental prototype (1. inlet, 2. press plate, 3. photodeformable material, 4. outlet, 5. pump membrane, 6. pump chamber)

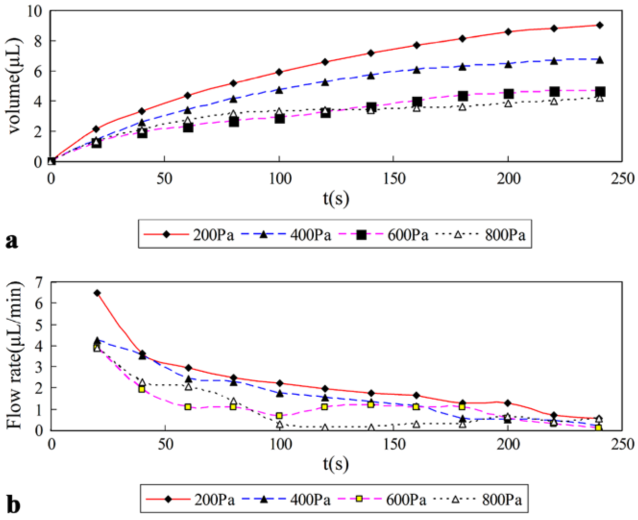


Fig. 7 **a** Changes of volume pumped in a stroke. **b** Change of flow rate in a stoke

membrane has lateral dimensions of 10 mm × 10 mm and a thickness of about 100 μm, the photodeformable film has dimensions of 8 mm × 8 mm × 20 μm.

In the experiments, the valves of the pump prototype are removed and the inlet is blocked. Therefore, the output volume will be that of the water pumped in a stroke. Several groups of experiments under different pressure are conducted, and the optical intensity is constant. The results of water volume pumped are shown in Fig. 7a while the change of flow rate is shown in Fig. 7b.

4 Discussions and conclusions

From the experiments, the following conclusions can be obtained.

(1) The flow rate of the water varies in a stroke of the pump membrane, which means, the bending speed of the laminated film decreases in this process.
(2) Under different pressure, the flow rate is different. The smaller pressure will lead to a higher flow rate and a larger volume pumped in a stroke.
(3) Under the pressure of 200 Pa, the volume pumped in a stroke is 9 μl. This is close to the simulation result in FEA software.

The following restrictive factors exist in our present study, which will be improved in the future work.

(1) The reversion of the film takes a relative long time, so that the frequency of irradiation is still low. With the development of this material, the bending speed will be faster and thus the bending process of the pump membrane can be completed in shorter time.
(2) The material of pump membrane is rubber, whose Young's modulus is 1.6 MPa. Considering there is some material such as PDMS as mentioned in the paper [10], of which the modulus is only 0.75 MPa, the deflection of the membrane can be much larger. Apply the parameters of PDMS in Ansys calculation, and we can obtain the deflection of the membrane is 0.67 mm, which is 1.3 times of the present result.

Since photodeformable material has remarkable deflection and shape memory effect, therefore, we believe that this material has great potential to be utilized in micropump and other relative applications. Our study proves that the laminated film sample of this material has sufficient ability to drive pump to work. The size of the prototype is in the range of millimeters for the present fabrication conditions in the lab, however, applications even on micrometer scale are possible through photolithography.

In future work, valve-less design or valves parts will be added into experiments, and further study will be carried on.

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