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Invited Paper

# Feedbacks in light-active soft materials

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## ABSTRACT

Imitating the self-regulated motions of natural species allows for novel applications in inanimate material systems. These applications include autonomous robotic systems, adaptive devices, and auto-energy harvesting. However, significant challenges exist in accurately controlling stimulus-induced deformations and establishing a reliable relationship between external energy fields and material deformations. In this study, we demonstrate that a simple light-triggered bending actuation in smart material systems based on liquid crystal elastomers is influenced by an opto-mechano-optical feedback mechanism. The pre-curved geometry enables enhance of light absorption upon photothermally induced deformation (from bent to flat), followed by a reduce of energy absorption upon further deformation (from flattening to bending toward the light). This strong nonlinearity in stimulus-induced deformability is governed by positive and negative feedback, and we experimentally verified these mechanisms using a thermal camera. Our results reveal the ubiquitous feedback nature of most light-active polymer systems.

**Keywords:** photoactuation, liquid crystal elastomer, feedback, self-regulated

## 1. INTRODUCTION

Optically-driven polymers are soft actuators that can perform pre-programmed shape-morphing in response to a light field stimulus[1]. Three key features make them suitable for soft micro-robot applications. Firstly, the fabrication of soft polymers enables the miniaturization of mechanically deformable actuators. Unlike pneumatic and dielectric actuators, which are typically the size of centimeters, active polymers can be fabricated to sizes below microns[2]. Secondly, the use of light stimuli enables fully wireless powering approaches, eliminating the need for cable connections[3, 4]. This is particularly convenient for realizing untethered robots that can move across different landscapes and inside confined and closed environments. Thirdly, these soft materials often possess multiple degrees of freedom of deformation[5]. By selecting the location of the light excitation, a manual control beam spot can activate deformation in the chosen area. The versatility of deformation freedom can also be increased by engineering bilayer architectures, programming molecular orientation, and even chemical composition[6-8].

Current soft robotic actuators, which are often large in size, benefit from programmable electronic circuits for system feedback. Feedback refers to a system where outputs are routed back as input signals. This helps to achieve precise control and establish reliable relationships between stimuli (such as electric voltage or current) and actuator shape changes. In comparison to conventional robotic actuators, light-driven polymers exhibit large nonlinearity in stimulus-deformation[9] and complicated shape-morphing kinetics[10], posing challenges for achieving precise robotic control. As a result, photomechanical polymer actuators are generally considered to lack precision in shape control and be deficient in programmability for controllable feedback that addresses the input (stimulus) and output (deformation) relationship.

In this work, we demonstrate that a simple light-triggered bending actuator is influenced by photo-mechanical feedback mechanism. Firstly, we introduce the general concept of feedback in light driven polymer actuator systems. Secondly, we present data on light-induced heat and deformation in a pre-curved liquid crystal elastomer actuator, in which both positive and negative feedback regimes are observed. Our results offer a straightforward explanation of feedback in light-driven soft actuators and facilitate the path towards precise control of light-driven polymer-based soft robots.

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# 2. RESULTS

## 2.1 The materials and feedback concept

A splayed liquid crystal elastomer (LCE) strip was prepared through a chain extension reaction[11]. Dispersed red 1 was thermally diffused into the polymer to enable photothermal absorption in the visible range. This material was chosen due to its linear heat-induced bending behavior. In a splayed LCE, the change in curvature 1/r (where r is the radius of the bending arc) or the bending angle is linearly proportional to the elevated temperature $\Delta T$ (see Fig. 1a). This bending is caused by the mismatch of thermal expansion strains on two surfaces of the material. The original shape of the material was pre-curved after removal from the fabricated cell and annealing at 50 ºC, which resulted from the elevated temperature during the polymerization process[12].

When the strip is heated by an incident light field, as shown schematically in Fig. 1b and c, the deformation (bending) of the strip results in reinforced or weakened light absorption, depending on the curvature of the strip. During the shape-morphing from a bent into a flattened geometry, the light absorption cross-section increases along with the light-induced deformation, resulting in positive feedback. When the flattened shape deforms into a curved shape (bending towards the light), the light absorption cross-section decreases along with the deformation due to the self-shadowing effect, resulting in negative feedback. Therefore, the light-induced deformation curve is anticipated to show nonlinearity that is influenced by both positive and negative feedback, unlike the linear curve shown in Fig. 1a.

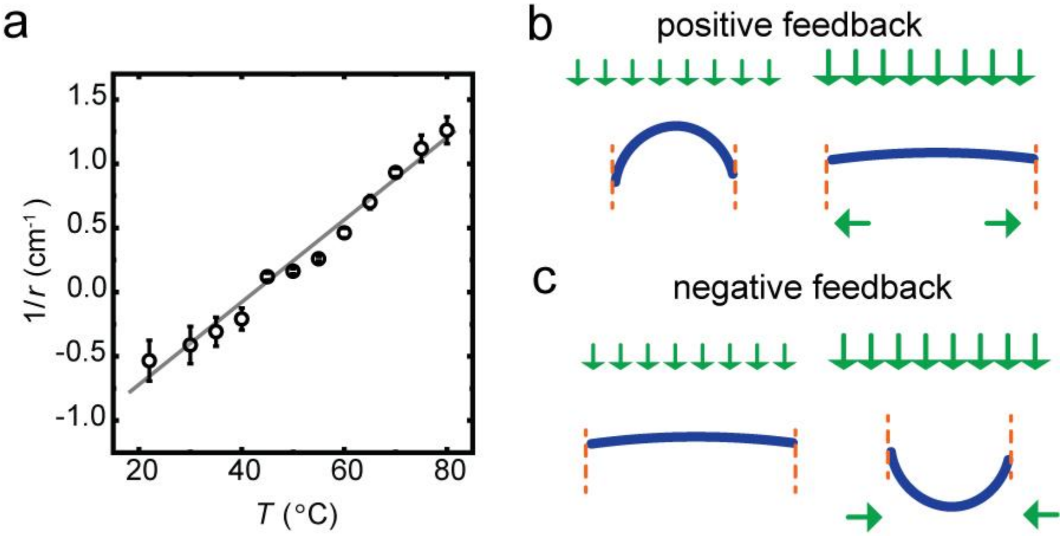

**Figure 1. The concept of photomechanical feedback.** (a) The heat induced deformation of a LCE strip. (b) Positive photo-mechano-optical feedback during the shape-morphing from bent to flat stage. (c) Negative feedback during the shape-morphing from flat to bent geometry.

## 2.2 Feedback observation in a photoactuator

To verify the above hypothesis, we measured changes in curvature upon increasing illumination intensity. A pre-curved LCE strip was placed in a uniform optical field that was spatially filtered and collimated using a Thorlabs ZBE4C telescope. As shown in Fig. 2a, the strip underwent deformation at thermal equilibrium upon static light irradiation. It unbent with increasing intensity until it was flattened around 125 mW cm$^{-2}$. We observed an initial increase in slope, which can be attributed to the positive feedback mechanism explained in Fig. 1. The curvature-intensity relationship became linear between 125 and 225 mW cm$^{-2}$, where the strip exhibited photoactuation at a small curvature (minimal feedback). Further deformation in the opposite direction resulted in self-shadowing, where negative feedback began to dominate. We also recorded the average temperature of the strip during light actuation, as shown in Fig. 2b. The data confirmed the nonlinear dependency of stimulus-induced deformation.

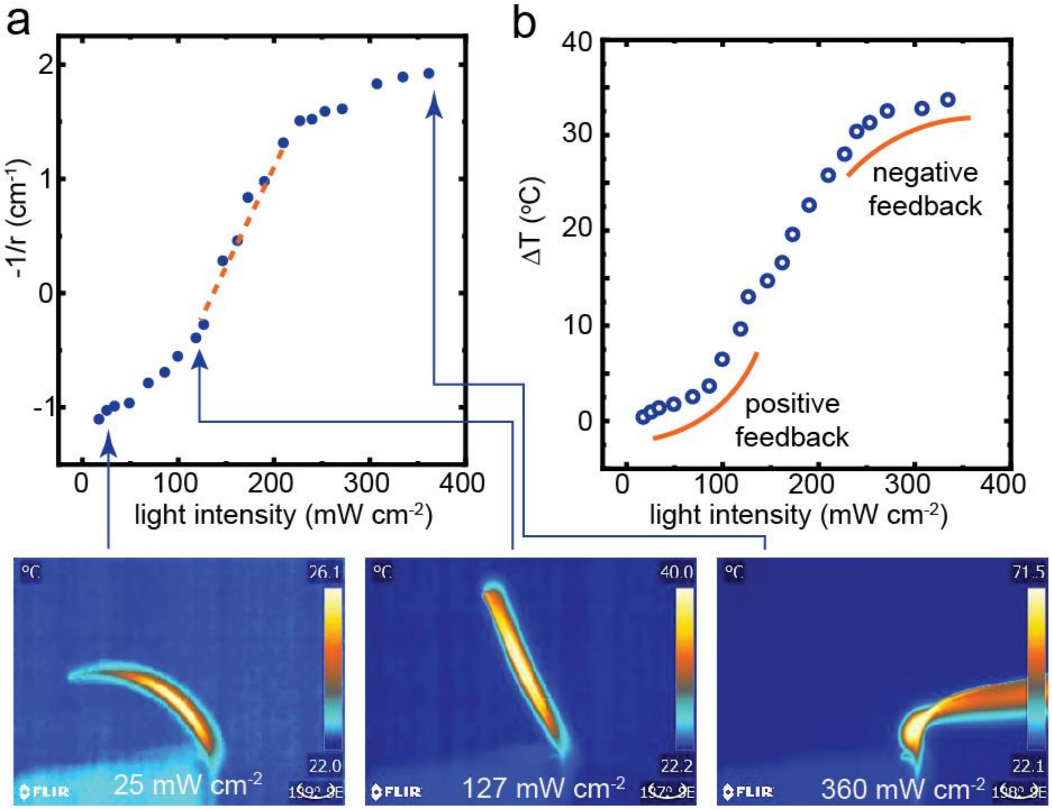

**Figure 2. Positive and negative feedback observation in photoactuator.** Deformation at the thermal equilibrium (a) and change of temperature (b) upon increase of illumination intensity.

## 3. DISCUSSION AND CONCLUSIONS

Although feedback is widely observed in light deformable polymer actuators, its discussion is rare in the literature. In our view, negative feedback can be used to describe systems with self- shadowing[13], in which a decrease in light absorption allows the system to establish an nonequilibrium condition by oscillating[14] or remain at equilibrium[10], - depending on the damping strength of the system. On the other hand, positive feedback allows a system to quickly change its state, for example, enhancing absorption to dictate "learned" actuation[15], closing or opening structures[12, 16], etc.

In this paper, we report that a simple light-triggered bending is influenced by an opto-mechano-optical feedback mechanism. As an example, we prepared a liquid crystal elastomer bending strip to demonstrate this mechanism. The pre-curved geometry enables enhanced light absorption during light-induced flattening and positive feedback from deformation to light field absorption. The shape-morphing from a flattened shape to a bent shape towards the light produces reduced light absorption as negative feedback. The change in temperature, measured using a thermal camera, corresponds with the data on light-induced deformation. Our results reveal the ubiquitous feedback nature of light-active polymers and help in better controlling light-driven soft micro-robots.

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