JMEMS Letters

Fabrication of LCE Microactuator Arrays Through Soft Lithography With Surface Alignment

Ke Li, Jae-Jun Kim, Jayer Fernandes, and Hongrui Jiang

***Abstract*— Liquid crystal elastomers (LCEs) offer potentially programmable actuation through precise molecular alignment, making them ideal for microactuators in soft robotics and optical systems. However, achieving precise microscale alignment for LCE actuator arrays through scalable microfabrication approaches has been challenging. This letter introduces a low-cost surface alignment method to fabricate LCE microactuator arrays, reducing the dependency on expensive equipment, improving accessibility and manufactuarability compared to existing studies using field-assisted alignment methods. Thermal actuation tests demonstrated strong thermal responsiveness and stability. Our method offers a superior approach to integrating LCE microactuator arrays with modern microfabrication processes, promising multitudinous applications in MEMS and beyond. [2024-0192]**

***Index Terms*— Liquid crystal elastomer, microfabrication, thermal actuation, microactuator arrays, surface alignment.**

I. Introduction

LIQUID crystal elastomers (LCEs) are versatile, responsive materials suited for actuators. Their capacity to be precisely controlled the alignment of embedded liquid crystal (LC) mesogens enables programmable actuation [1], [2], driving interest in LCE microactuators for miniature robotics and biomedicine, including microgrippers [3] and microneedles [4]. However, achieving microscale alignment remains challenging, often limiting these devices to simple, restricted motions [5], [6]. Existing methods, such as magnetic field alignment and preprogrammed laser-induced actuation, require costly equipment and cannot achieve individual alignment for separate microactuators, restricting accessibility and scalability [7], [8]. Surface alignment, achieved by creating directional substrate cues, shows promise for establishing distinct micro-scale domains and complex actuation [9], [10], but conventional techniques are not well-suited for isolating and independently actuating individual LCE microscale units.

Here, we present a modified surface alignment method that addresses these challenges. Our approach enables microscale fabrication of LCE microactuator arrays and provides opportunities for individual unit-level (called microblocks) alignment control using simple actuation. By enhancing both accessibility and scalability, this technique broadens the potential applications of LCE microactuators in advanced microsystems and soft robotics.

Received 23 October 2024; revised 15 December 2024; accepted 25 February 2025. This work was supported by U.S. National Institute of Biomedical Imaging and Bioengineering of U.S. National Institutes of Health under Grant R01EB019460. Subject Editor A. Ansari. *(Ke Li and Jae-Jun Kim contributed equally to this work.) (Corresponding author: Hongrui Jiang.)*

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Digital Object Identifier 10.1109/JMEMS.2025.3546852

II. Fabrication

Our method of fabricating LCE microactuator arrays involves a multiple-step process that integrates soft lithography and surface alignment techniques, enabling precise alignment control over the LCE microstructures while eliminating the need for expensive equipment. The following outlines the specific steps used in this fabrication process.

A. Mold Fabrication for LCE Patterning

The fabrication cell includes a perfluoropolyether (PFPE) mold to pattern the LCE and address the adhesion issue in existing surface alignment methods, and two Elvamide-coated glass substrates with grooves for mesogen alignment.

To create the PFPE mold, SU-8 2010 photoresist (Kayaku Advanced Material) was spin-coated onto a silicon wafer, UV-exposed through a photomask, baked, and developed, forming a 45-μm-thick SU-8 mold (Fig. 1(a)). Polydimethylsiloxane (PDMS, Sylgard 184, Dow) prepolymer, mixed with curing agent (10:1), was degassed, poured over the FOTS-treated (1H,1H,2H,2H-perfluorooctyl trichlorosilane, Sigma-Aldrich) SU-8 mold, cured, and peeled off, resulting in inverse PDMS patterns (Fig. 1(b)). A 20-nm Ag layer was deposited on and selectively removed (Figs. 1(c) and 1(d)), adjusting surface hydrophilicity for PFPE mold preparation.

The substrate patterning involved spin-coating a 0.15 wt% solution of polyamide (Elvamide 8061, Celanese) in methanol onto a glass substrate (2000rpm 60s) to form a uniform thin film. The Elvamide layer was then subjected to a rubbing treatment (HO-IAD-BTR, Holmarc) with a 2000 rpm rotation speed and a pile impression of 300 μm to induce the grooves for mesogen alignment (Fig. 1(e)). These microgrooves ensure effective mesogen alignment through physical guidance and confinement and minimize steric hindrance.

PFPE was chosen as the intermediate thin mold for LCE patterning. The PDMS patterned structure was glued on a Elvamide-coated glass using diluted thin PDMS. A mixture of PFPE and photo-initiator (4wt%, Darocur 1173, Sigma-Aldrich) was injected from one side of PDMS molds and placed under vacuum to fill the patterns (Fig. 1(f)). The assembly was exposed to UV light for 20 minutes in a nitrogen environment to cure and develop the PFPE film (Figs. 1(g) and (h)). Optical microscopy is used to ensure accurate pattern replication from PDMS to PFPE.

B. LCE Micro-Block Arrays

The LCE microactuator array was fabricated using the patterned PFPE film as the mold and two Elvamide-coated glass pieces as top and bottom substrates. The LCE mixture

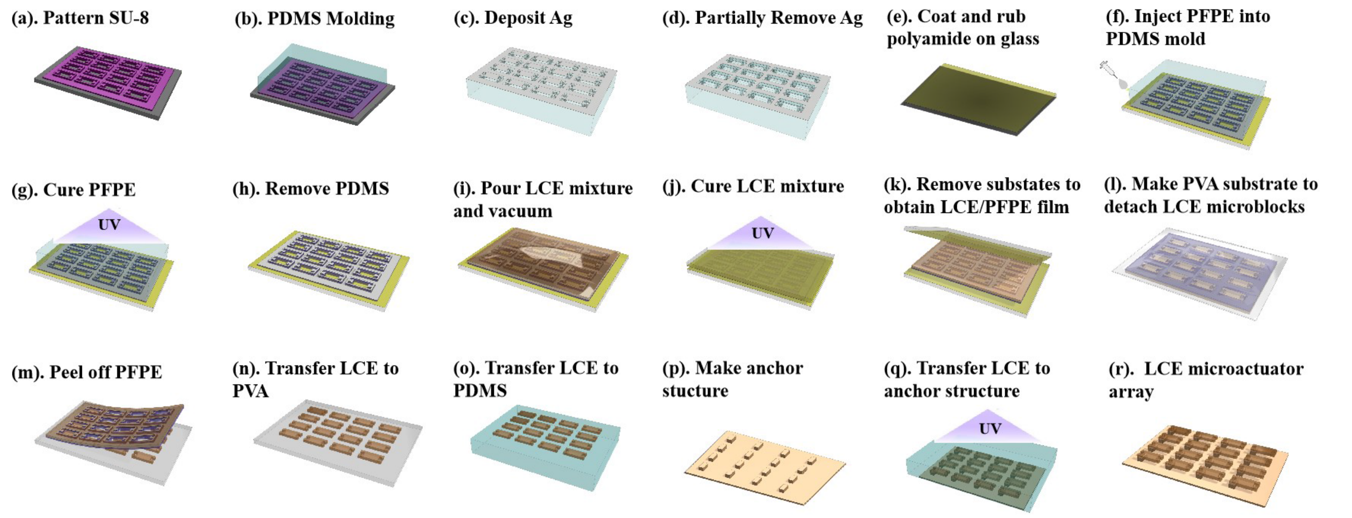

Fig. 1. Fabrication process of LCE microactuator array. (a)-(h) mold preparation for LCE patterning. (i)-(r) LCE microactuator array fabrication and transfer to anchors.

composed of M1 (87.12wt%, 4-(6-Acyloxy-hex-1-yl-oxy)phenyl-4-(hexyloxy)benzoate, Synthon Chemicals), M2 (11.88wt%, 1,4-Bis-[4-(6-acryloyloxy-hexyloxy)benzoyloxy]-2-methylbenzene, Synthon Chemicals), and photo-initiator (1wt%, DMPA, Sigma-Aldrich), was melted and mixed at 100°C and then poured and evenly spread onto the PFPE-patterned substrate. The substrates were subjected to a brief vacuum to remove trapped air (Fig. 1(i)). After reheating the substrate on a hot plate to 100°C, the top Elvamide-coated glass was carefully placed over the LCE mixture, and two 200g weights were applied to ensure uniform film thickness. The assembly was gradually cooled from 100°C to 55°C, and the LCE film was finally cured through UV exposure with an intensity of 20 mW/cm^2 for 20 minutes (Fig. 1(j)).

After UV exposure, the PFPE/LCE film was detached from both substrates by soaking the entire assembly in warm water at 60°C overnight (Fig. 1(k)). The Elvamide residue on the PFPE/LCE film was removed by a 1-minute soak in methanol followed by rinsing and drying. The cleaned PFPE/LCE film was placed onto a PDMS substrate, and a 4 wt% polyvinyl alcohol (PVA) solution was dispensed onto the PFPE film surface and then dried on a hot plate at 60°C for 5 hours. Finally, the PFPE film was gently peeled off, successfully transferring the LCE patterns onto the PVA layer (Figs. 1(l), (m) and (n)).

The LCE microactuators were then transferred onto pillar anchor structures. First, the PVA film with the LCE microactuators was placed on a PDMS substrate. Water was dropped on the film to dissolve the PVA sacrificial layer and release the LCE micro-blocks onto the PDMS layer, followed by drying with a nitrogen blow gun (Fig. 1(o)). The pillar anchors were formed by pouring a photoadhesive (NOA86H, Norland Products) onto a PDMS mold and curing under UV. Then, another NOA86H thin layer was blade-coated onto the PDMS microstructures and contact printed onto the cured pillar anchors as glue (Fig. 1(p)). The LCE micro-blocks on PDMS substrate were carefully aligned with the pillar structures under a microscope and placed onto them using a linear stage. Finally, the assembly was cured under UV light, securing the LCE micro-blocks to the anchor structures (Figs. 1(q) and (r)).

III. Experiment

The experimental evaluation of the LCE microactuator arrays was conducted through a series of tests designed to verify their alignment and assess their thermal actuation capabilities. These experiments validate the effectiveness of the surface alignment method and demonstrate the practical functionality of the microactuators under various conditions. The following sections outline these experiments in detail, highlighting the key observations and results.

A. Alignment Test

An optical microscopy test was conducted using a polarized optical microscope to confirm the desired optical properties and alignment of the LCE microactuator arrays. The mechanism underlying this test relies on the birefringent nature of LCEs, which exhibits different refractive indices depending on their molecular orientation. When polarized light passes through the LCE sample placed between crossed polarizers, the interaction of light with the material reveals details about its molecular alignment.

When the polarizer, analyzer and expected LCE alignment direction were aligned at 0°, light passed through the LCE and the background with the same intensity (Fig. 2(a)). After rotating the polarizer by 90°, no light was transmitted through either LCE or the background (Fig. 2(b)), indicating effective molecular alignment. At a 45° rotation of LCE microactuators, light was transmitted through the LCE while the background remained dark (Fig. 2(c)), confirming the influence on light transmission by the alignment, in consistence with Malus's Law.

B. Thermal Actuation Test

The thermal actuation test examined the dimensional changes of the microactuators under controlled thermal cycles, providing insights into their thermal responsiveness and reliability. Initially, the microactuator arrays were at 35°C, and their dimensions were recorded using optical microscopy (Figs. 2(d) and (e)). The temperature was systematically increased to 60°C, 80°C, 100°C, 120°C, and finally 140°C, followed by a cooling cycle with measurements taken at each step to monitor the dimensional changes of the free-standing parts of the microactuators (Fig. 2(h)). At the highest temperature of 140°C, a contraction in length of approximately 12% was observed, demonstrating the thermal actuation capability of the microactuators (Figs. 2(f) and (g)). This contraction is closely related to the alignment direction of the LCE. The cooling cycle showed the same actuation features at each temperature step, indicating the stability of the LCE microactuators. This experiment confirms the thermal actuation functionality of the LCE microactuator arrays.

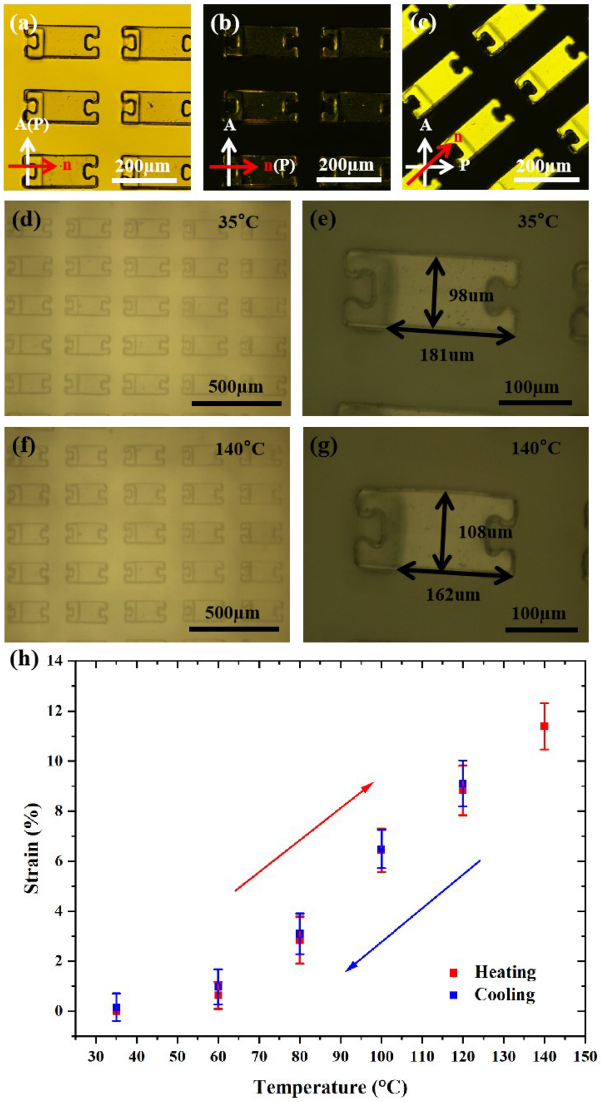

Fig. 2. (a)-(c). Alignment test of LCE microactuator array characterized by optical microscope with analyzer (A), polarizer (P) and alignment direction (**n**) at different angles. (d)-(h). Thermal actuation test of a 5×5 microactuator array with dimensions of LCE micro-block at 35°C and 140 °C.

IV. Conclusion

The fabrication of LCE microactuator arrays using surface alignment has proven to be a viable and efficient method, offering precise control over the alignment and actuation properties of LCEs at the microscale. Our experimental results confirmed the successful alignment of LCE microactuators and demonstrated their thermal actuation capabilities, highlighting the potential of these arrays for use in advanced MEMS applications. The accessibility and scalability of the surface alignment method makes it a promising approach for future developments in LCE-based technologies, enabling the creation of highly versatile and responsive microactuation systems. Further research will focus on studying and improving the alignment uniformity, and exploring more complex alignment patterns and independent actuation in individual LCE microactuator for broader applications.

Acknowledgment

This research utilized NSF-supported shared facilities at the University of Wisconsin–Madison.

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