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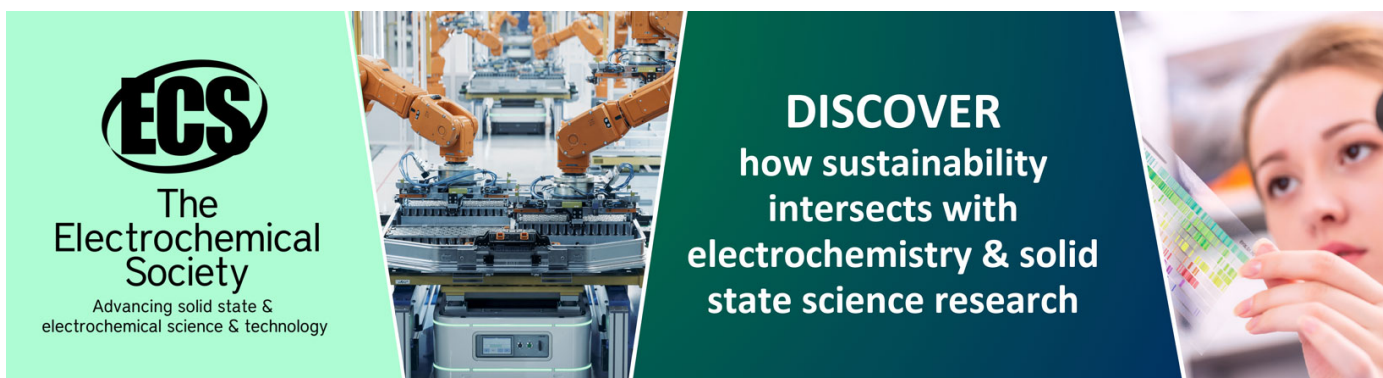
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MEMS-compatible structuring of liquid crystal network actuators using maskless photolithography

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Abstract

We present a method to structure liquid crystal network actuators based on selectively polymerizing the network without any physical or hard masks in a process compatible with microelectromechanical system (MEMS) technology. The standard glass-cell filling technique is used to generate the actuator films; subsequently, selected areas are exposed to light and thus polymerized to structure the actuators. No further machining, such as laser cutting, is necessary. The polymerization pattern is defined by projection using a digital micromirror device-based optomechanical setup, with a resolution ranging from 1 to 2 mm. These processes are used to structure photothermally and photochemically stimulated actuators, which may thus be fabricated with high throughput and easily integrated with MEMS devices.

Supplementary material for this article is available [online](#)

Keywords: maskless photolithography, selective polymerization, photoactuation, liquid crystal networks

(Some figures may appear in colour only in the online journal)

1. Introduction

The use of soft-matter materials for actuating microelectromechanical system (MEMS) devices has a rich history [1] and has included materials such as dielectric elastomers [2–4], hydrogels [5], conductive polymers [6, 7], and liquid crystal elastomers (LCEs) [8]. Considerable work has been done in the past few decades on integrating these soft-matter-based actuators into MEMS, resulting in successful implementation of components such as tunable lenses [9], tunable irises [10],

miniaturized valves [11, 12], micropumps [4], tactile displays [3], and grippers [13].

Although each of these actuation mechanisms has its own benefits and limitations [1, 14], liquid crystal elastomers or networks (LCEs or LCNs) actuators are particularly attractive, as their mechanical properties can be easily tuned by modifying the network [15, 16] and the actuation direction is defined by the orientation of liquid crystals, thereby opening up the possibility of actuation movement in multiple directions and including those out-of-plane [17, 18]. Another advantage of the use of LCEs or LCNs as actuators is that it is possible to actuate the material using different stimuli such as heat, electric fields, light, or humidity [8, 15, 19, 20].

LCEs or networks are crosslinked polymer networks with reactive mesogens (monomers) embedded into them. These materials exhibit the properties of an elastomer combined with the long-range orientation of mesogens, thus coupling

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the order of mesogens with the mechanical stress. Exposing the network to stimuli leads to disordering of the network, resulting in anisotropic thermomechanical deformation.

The conceptual difference between the term *elastomer* and *network* in the liquid crystal context lies in the different crosslink densities, leading to difference in elastic modulus (E), glass transition temperatures (T_g), and strain rates. In contrast to LCEs, LCNs have moderate to high crosslink densities leading to higher E , higher T_g , and lower strain rates [15]. As actuators for MEMS devices that can be controlled via light, LCEs or LCNs show great promise, as their properties (such as the required wavelength for actuation, work density, or strain rate) are a function of the chemical system and can thus be easily modified by depending on the final application [15, 20]. However the available fabrication processes for LCNs have so far hindered the proper integration of these materials with MEMS devices.

LCNs are predominantly fabricated using cells or molds, where the orientation of the mesogens is defined either by magnetic fields, surface rubbing, uniaxial stretching of the material or photoalignment [21]. In these processes, each sample must be mechanically peeled off and cut into the desired shapes for the final structure, making integration with MEMS devices challenging. To address these limitations, additive manufacturing (AM) processes such as direct ink writing [17, 22–24] and two-photon polymerization-based direct laser writing [25–28] have recently been used to obtain thermally-actuated LCE/LCN actuators with thicknesses in the millimeter range. The main drawback of these AM processes is that the alignment of the mesogens is limited to one direction, since the orientation of the mesogens is defined by the shear forces and/or elongational flow along the printing path [22].

In addition to using AM processes, other approaches such as photolithography and then subsequent etching or polymerization with multiple exposures have also been explored to pattern LCN/LCE-based actuators [13, 29–31]. Although LCE/LCN actuators could be successfully patterned using these processes with resolution down to tens of microns, the major disadvantage with these methods is swelling of the polymer network due to usage of organic solvents during structuring, thereby leading to poor adhesion with the substrate and loss of director orientation in the network. The issue of network swelling can be eliminated by using specialized fluorinated solvents with orthogonal solubility instead of organic solvents, but at the expense of final LCE thickness [29]. Due to poor etching selectivity of 0.43:1 between LCE and fluorinated photoresists, actuators with thickness in the range of 600–700 nm could be obtained. As reported by authors in [29], no actuation could be obtained from LCE films with such low thickness.

We address these challenges for fabricating LCEs/LCNs based actuators here by presenting a MEMS-compatible fabrication technique in which structuring of the actuator is achieved by spatially varying the polymerization of the network using a maskless lithography technique. Using a digital micromirror device (DMD)-based optomechanical setup, the

network is patterned in a pixel-by-pixel fashion [32], thereby making the use of any physical masks, photoresists or stencils obsolete. Furthermore, to support the functionality of the structuring technique, we will demonstrate actuation using both photothermal and photochemical mechanisms, wherein the actuator can undergo complex light-induced shape changes.

2. Actuator fabrication

The fabrication process for the LCN actuators is summarized in figure 1(a). The essential steps in this process are the photoalignment (section 2.2) and maskless photolithography (section 2.3), which we describe in more detail below.

2.1. Materials

Figure 1(b) illustrates the chemical structures of compounds used in this work for fabricating the LCN actuator. Actuators are made by photopolymerization of mixtures consisting liquid crystal mesogens, crosslinkers, photosensitive elements, and photoinitiators. The measured absorption spectra of the photosensitive molecules for light-driven actuation are shown in figure 1(c).

For light-driven actuation of LC network, both photothermal effect and photochemical mechanism are used in this work. The difference in the actuation mechanism stems from different lifetimes of *cis*-isomers of used molecules M5 and M8, which are in the order of hours and seconds, respectively [33].

Molecules M2, M4, M7 and M8 are used to form photothermally actuated LCN actuator, in which a commercially available azobenzene-derivative Disperse Red 1 acrylate is used. Upon illumination, due to its short *cis*-lifetime, the molecules undergo fast *trans-cis* isomerization, leading to heat generation, and subsequent shape change of actuator [34, 35]. Molecules M2, M3, M4, M5 and M6 are used to form the photochemically actuated LCN actuator, in which, upon illumination, the bent shape of the *cis*-isomer disrupts the order of LC network, resulting in shape change of the actuator. Due to long lifetime of this *cis*-isomer, this shape change is preserved even after turning off the light and the original shape can be recovered by illumination with another wavelength or via thermal relaxation [33]. Detailed information on the chemical structures and composition used for each actuator can be found in the supplementary information, S1.

2.2. LC film generation and photoalignment

The LCN films are generated using the glass-cell filling technique. For this, glass substrates (24 × 24 mm) are cleaned by sonication in acetone, isopropyl alcohol, and de-ionized water for 5 min each and subsequently dried with nitrogen. This is followed by O₂ plasma treatment with a gas flow rate of 50 sccm at 0.2 mbar pressure for 5 min.

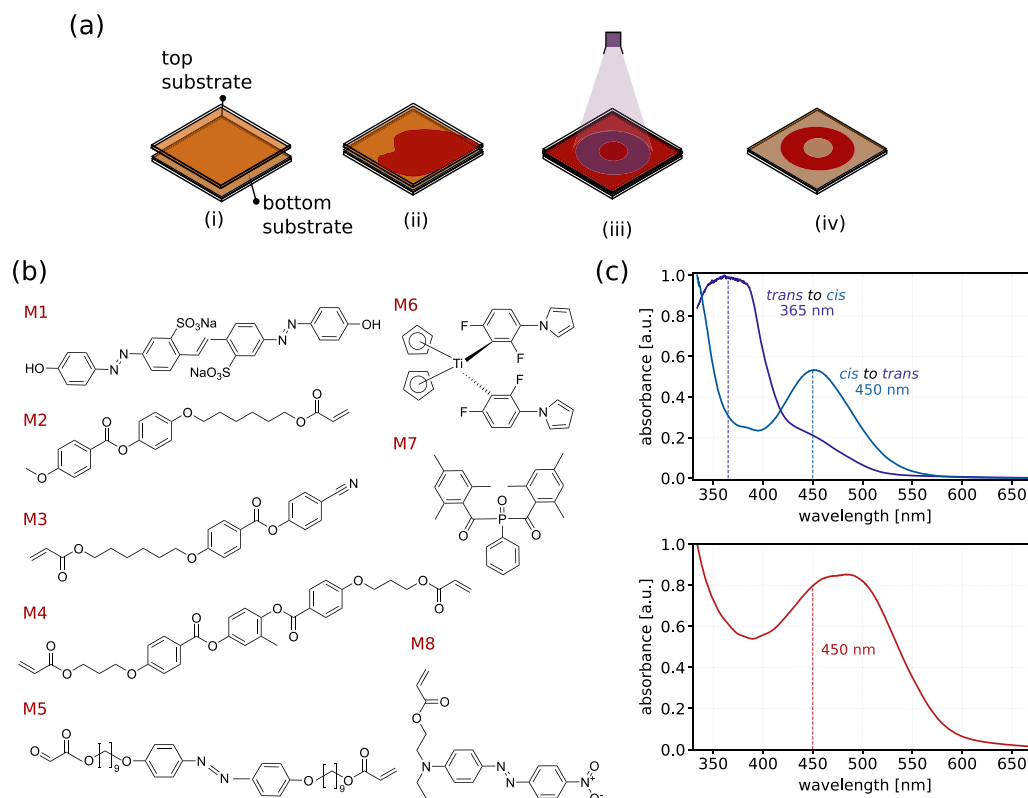


Figure 1. (a) Schematic illustration of structuring process for LCN actuator with maskless photolithography. (i) The top and bottom glass substrates are photoaligned with Brilliant Yellow, and are assembled to form a glass-cell, (ii) LC mixture is filled inside the glass-cell. (iii) After filling of LC mixture, a pattern is projected via spatially structured light for selectively polymerizing the network. (iv) As the last step, the glass-cell is opened and unpolymerized areas are removed by solvent immersion. (b) Chemical structures of the molecules used in this study for fabricating the LCN actuator. (c) Absorption wavelength measured in a 10 μm thick film of azobenzene crosslink M5 (top) and Disperse Red 1 Acrylate M8 (bottom) as photothermal dopants. The dotted lines indicate the wavelength used in the study for excitation.

The alignment of liquid crystal mesogens is done with photoalignment technique, allowing alignment of the mesogens at arbitrary angles in one plane, thereby enabling the multi-directional motion of LCNs in more than one plane [32, 36–38]. The custom-built DMD-based optomechanical setup used in this work allows us to align the LC mesogens in a pixel-by-pixel fashion, with a resolution down to 20 μm [32].

For photoaligning LC meogens, 1 wt% solution of Brilliant Yellow (BY) in DMF (N,N-Dimethylformamide) is prepared and filtered through 0.2 μm PTFE syringe filter. 50 μl of BY solution is then spincoated at 3000 rpm for 20 s and is dried on a hotplate at 90 $^{\circ}\text{C}$ for 5 min. This 5–20 nm thick BY layer acts as the photoalignment layer for alignment of the reactive mesogens. Substrates spin-coated with BY are then exposed to linearly polarized 450 nm light [32]. To obtain bending motion of the actuator, the top and bottom substrates of a glass-cell are aligned at 0 $^{\circ}$ and 90 $^{\circ}$ with respect to the polarizer, resulting in twist-bend alignment configuration [39]. The obtained 90 $^{\circ}$ twist-bend alignment between two parallel polarizers can be found in the supplementary information, S4.

The LC mixture is prepared by dissolving the monomers in dichloromethane in a glass vial and is filtered through 0.2 μm PTFE syringe filter. The mixture is magnetically stirred at 80 $^{\circ}\text{C}$ for 4 h to remove the solvent. To ensure that the solvent

has completely evaporated, the mixture is then put in vacuum oven at room temperature for another 2 h. Glass-cells with different spacing thicknesses are fabricated using double-sided tape (Nitto Deutschland GmbH). The cells are then filled with above-prepared LC mixture at 90 $^{\circ}\text{C}$ via capillary action. The cells are brought to their nematic phase 50 $^{\circ}\text{C}$ at 2 $^{\circ}\text{C min}^{-1}$. The aligned LC films in the cells are then ready for structuring using photopolymerization as described in the next section.

2.3. Actuator structuring

The subsequent structuring of the LCN actuator is done by selectively polymerizing the network using a maskless photolithography technique. By spatially varying the illumination at the appropriate wavelengths, it is possible to structure the network in any arbitrary shape. Following exposure, the non-polymerized areas are developed in a solvent and thus removed. A schematic description of the process is given in figure 1(a).

The process for defining the pattern for polymerization is same as that for defining the pattern for aligning the BY molecules [32]. The desired image pattern is projected via a DMD projector onto the substrate. By changing the illumination pattern we may structure the network in any

arbitrary shape in a pixel-by-pixel fashion. We employ the same projection setup for aligning the reactive mesogens and for structuring the network; the only major difference is that for polymerization the angle of polarizer is kept at 0° . We do not expect any effect of polarized light on the azobenzenes during polymerization.

After developing, the structured actuator may then be glued to a 3D-printed substrate via a stamp-and-stick technique [40].

3. Results and discussion

3.1. Maskless photolithography

As a proof of concept, different patterns, as illustrated in figures 2(a1)–(a4) were projected onto the substrate, wherein areas corresponding to the black regions will be polymerized. The resulting patterns are shown in figures 2(b5)–(b8) wherein the non-polymerized areas have undergone spherulite-like structure formation, confirming the successful selective polymerization of LC network.

The projected image size with the optomechanical setup on the image plane is 4.5 mm. In figures 2(a2)–(a4), the projected image with area of $18 \times 18 \text{ mm}^2$ is split into a matrix of 4×4 , yielding 16 squares. Then, each sub-square is individually illuminated and, with stitching, an area of $18 \times 18 \text{ mm}^2$ is thus selectively polymerized.

To quantify the spatial resolution for polymerization, the pattern shown in figure 2(a4) having different square side lengths and spacing between the squares was projected onto the substrate. Again, the black squares correspond to the areas which are polymerized. Figure 2(b8) illustrates the obtained polymerized structure with $100 \mu\text{m}$ thickness. The polymerized areas that were projected with squares with side lengths less than 1 mm do not have sharp edge (resembling almost a step function), hence observing polymerization in the unwanted areas. This is also evident from the figure 2(b5), wherein the polymerized areas are not of 1:1 size of their projected areas. From this observation, we can conclude that minimum achievable size for structuring the $100 \mu\text{m}$ thick actuator with the current optomechanical setup is in the order of 1–2 mm. We believe this difference between projected image size and obtained polymerized area, and thereby the limitation on minimum structure size, is not from the optical setup, but rather from how the chain-initiation reactions along the thickness of actuator take place. In comparison, using the process for the much thinner spin-coated LCEs ($2\text{--}5 \mu\text{m}$), the resolution can be on the order of few hundred microns [41]. Hence the structuring resolution is dependent on the thickness of material, as the bulk chain-initiation reactions probably do not allow for the same resolution for selectively polymerizing the material as can be obtained using standard photolithography and etching [29] or with two-photon polymerization [25, 28, 42]. It might be possible to increase the spatial resolution by using stronger demagnifying projection optics with appropriate numerical apertures or by using a DMD with smaller pixels, which would allow patterning with smaller pixel sizes.

For demonstrating the maskless photolithography as summarized in figure 2, LC network containing molecules M2, M4, and M7 with $100 \mu\text{m}$ thickness was used. To further quantify the selective polymerization procedure for LC mixtures for both photoactuation mechanisms, photothermal and photochemical, the respective LC mixtures (supplementary information, S1) with different thicknesses were also selectively polymerized. The resulting exposure doses are summarized in figure 3.

For the photothermally-driven actuator, the photoinitiator (figure 1(M7)) has an absorption range 350–410 nm and for the photochemically-driven alternative, the photoinitiator (figure 1(M6)) has a broad absorption range 250–550 nm (see supplementary information, S2). An LED light source with an emission wavelength of 365 nm is thus used for polymerizing the network for photothermal actuation and an LED with an emission wavelength 554 nm is used for polymerizing the network with photochemical actuation. To avoid activation of azo-crosslinker, a bandpass filter is used to block wavelengths shorter than 520 nm.

As summarized in figure 3, the time required for polymerizing both LC mixtures used in this work is variable. This variation is primarily due to three main factors: photoconversion efficiency of photoinitiators; light intensity reaching at the image plane; and the ratio of acrylates to diacrylates in the mixture. The optical power reaching the sample/image plane for 365 nm LED was $90 \mu\text{W}$, leading to higher exposure times. The power of the 554 nm LED was $25 \mu\text{W}$ at image plane, reduced to avoid overexposing the entire surface.

After selective polymerization, the glass-cells are submerged overnight in DI water at room temperature to easily release the films. After opening the cell, the substrate is submerged in diethyl ether to develop the unpolymerized areas. Diethyl ether is chosen to avoid any potential swelling of the polymerized network, which is a common issue with other organic solvents such as toluene and chloroform. The developing time for a $3 \mu\text{m}$ thick film is about 5 s and for $100 \mu\text{m}$ thick LCN actuator, the development time varies from 2–3 min. Finally, the obtained films are rinsed with DI water and subsequently dried with N_2 gas.

To anchor the LCN films, a 3D-printed substrate (Form 3+, FormLabs Inc.) is used as a prototype. To attach the actuator to the printed substrate, Araldite 2020 adhesive is used. This adhesive has low viscosity, making it easier to spin-coat and to achieve a variable thicknesses by changing the spin speed. In this work, 10 ml of the adhesive mixture is spin-coated at 5000 rpm, resulting in thickness of $4 \mu\text{m} \pm 0.5 \mu\text{m}$. The 3D printed substrate which also acts as a stamp, is dipped into the spin-coated glue and then is attached to the LCN actuator. The curing of adhesive is done at room temperature for 12 h. With this method, it is possible to achieve a uniform layer of adhesive between actuator and substrate.

The above results that we have mentioned demonstrate that by using DMD-based projection setup to structure the LCEs/LCNs based actuators does eliminates the need for using static masks which are cumbersome to create or the need of specialized photoresists that are not easily available. Using our approach of maskless structuring also allows to change the

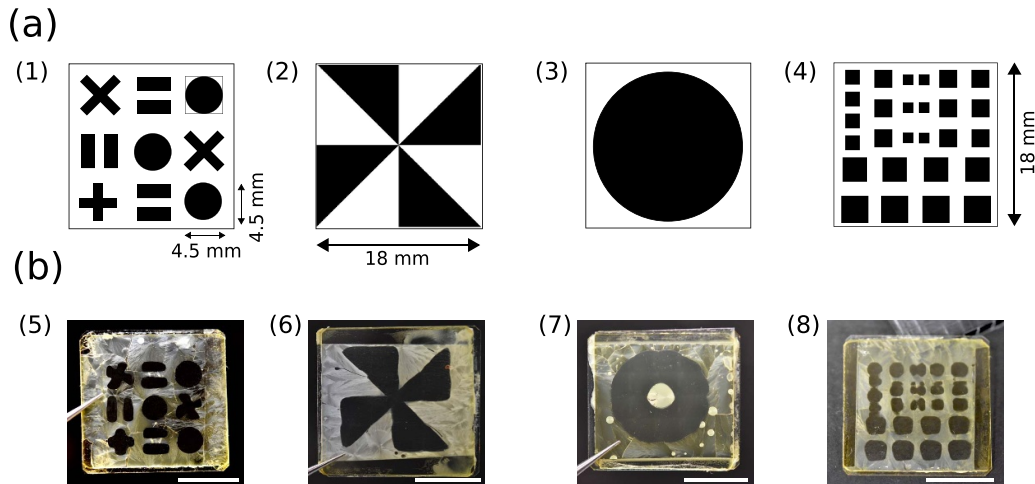


Figure 2. (a) Patterns projected via DMD (1–4) on the glass-cell wherein the areas shaded in black are exposed to light and hence gets polymerized. (b) The corresponding images of the selectively polymerized network (5–8) illustrates the successful selective polymerization of LC mixture inside a $100\ \mu\text{m}$ thick glass-cell. The unpolymerized areas have undergone spherulite-like formation. All scale bars in images (5–8) correspond to 1 mm.

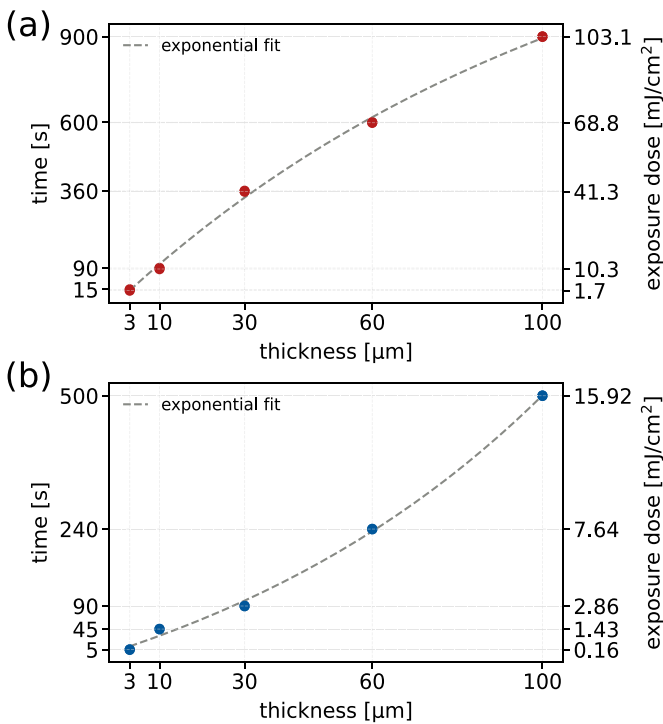


Figure 3. Required minimum exposure time with a projection area of $4.5 \times 4.5\ \text{mm}^2$ for selectively polymerizing the LC networks as a function of LC film thickness (a) LC mixture for **photothermally driven actuation** containing photoinitiator M7 polymerized with a 365 nm LED and (b) LC mixture for **photochemically driven actuation** containing photoinitiator M6 polymerized with a 554 nm LED.

projected pattern onto the DMD within a few seconds, thereby decreasing the required time for processing.

Moreover, additional waiting times in-between the processing steps do not pose any limitation to the above

mentioned fabrication capability. For instance, by curing the adhesive at $100\ ^\circ\text{C}$, the curing time can be shortened from 12 h to a mere 15 min. However, curing at higher temperatures was not done in our work to avoid any potential thermal actuation. Furthermore, to speed up the release of structured films from the glass-cells, it is possible to use water-soluble sacrificial layers such as PVA or Dextran before spin-coating the photoalignment layer, so that upon submerging the glass-cells in DI water, the dissolution of the sacrificial layer will shorten the waiting time [29, 43].

Additionally, the fabrication capability was demonstrated on small substrates ($24 \times 24\ \text{mm}^2$). However, the optomechanical setup allows stitching the patterns over a full 100 mm wafer. Hence, both techniques, photoalignment and selective polymerization, can be easily scaled up to fabricate the actuators on a full 100 mm wafer. In addition to this, it is also possible to combine standard microsystem fabrication techniques with these processes to further increase the compatibility of LCE/LCN based actuators with the MEMS technology.

3.2. Actuation behavior

Using the processes and materials described above, an array of actuator structures was manufactured and characterized to demonstrate the utility and practicality of these new LCN fabrication processes. By taking inspiration from previously done work [38, 44, 45] for actuating LCEs/LCNs, in this section we describe the actuation characteristics of structured actuators in more detail.

3.2.1. Photothermal actuation. To demonstrate the feasibility of the methods for aligning, fabricating, and structuring the LCN actuators described above, the LC mesogens are aligned and selectively polymerized in the patterns shown in figure 4(a1). The structure is aligned in 90° twist-bend fashion,

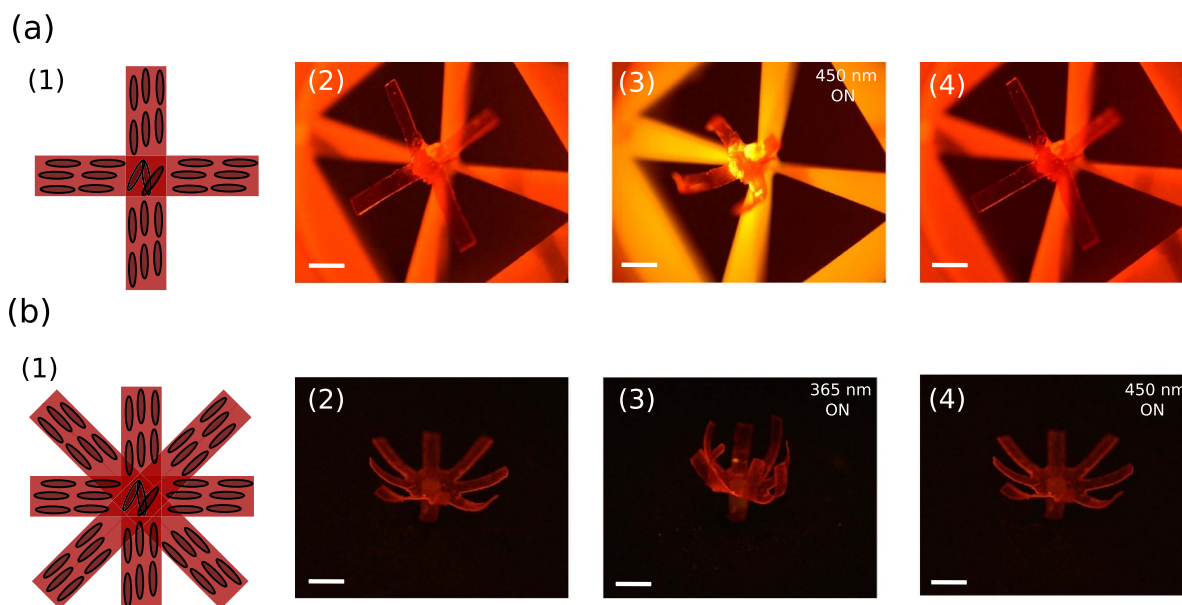


Figure 4. (a) **Photothermal actuation** (1) Schematic of mesogen orientation facing the illumination and pattern for selective polymerization, (2–4) snapshots of photothermal actuation illustrating the actuation and relaxation of the actuator when irradiation with 450 nm is turned on and off. (b) **Photochemical actuation** (1) Schematic of mesogen alignment facing the illumination and corresponding pattern for selective polymerization, (2–4) snapshots of photochemical actuation when when irradiation with 365 nm and 450 nm is turned on and off. All scale bars corresponds to 2 mm.

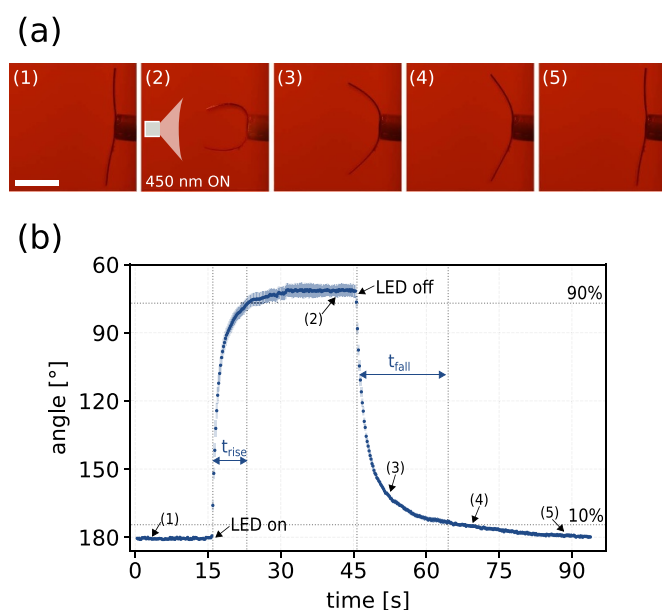


Figure 5. (a) Series of images showing different actuated states of a $60\ \mu\text{m}$ thick photothermally driven LCN actuator. Image 2 shows the actuated state when LED is switched on. Scale bar corresponds to 5 mm. (b) The transient step response of the bending angle for $81\ \text{mW cm}^{-2}$ irradiation with 450 nm. Each data point corresponds to the average value of ten actuation cycles and the corresponding error bars represents sample standard deviation ($n = 10$).

meaning that the top and bottom substrates at aligned orthogonally with respect to each other. Due to the 90° variation in the orientation of LCs, the top and bottom surface will experience non-uniform strain rates upon actuation, resulting

in an enhanced bending motion [39]. Videos demonstrating this actuation may be found under supplementary material.

After assembling the glass-cell with $60\ \mu\text{m}$ spacing and filling in the LC mixture for photothermally driven actuation, the precursor is selectively polymerized and developed to yield the cross as shown in figure 4(a1). Figures 4(a2)–(a4) shows the photothermal response of the actuator when illuminated with 450 nm at $150\ \text{mW cm}^{-2}$.

In this actuator, as briefly noted above, upon illumination at room temperature, the azobenzene derivative, Disperse Red 1 acrylate, absorbs light and due to its short *cis*-lifetime, on the order of a few hundred milliseconds [33], the light absorption leads to fast isomerization and subsequently heat generation. This heat is transferred to the LC network, resulting in disordering of the network and subsequent shape change of the LCN. When the LED is switched on, within less than 5 s, the four flaps of the actuator bend and as soon as light illumination is turned off (figure 4(a4)), the actuator retains its original shape, demonstrating reversible actuation.

To more fully characterize the mechanical deformation of LCN actuators, a set of photographs as shown in figure 5(a) is used to analyze the changes in the bending angle. This characterization also helps to analyze how the material will behave when it is constricted at the center, for example to function as a micro-gripper. A 90° twist-bend LCN film is thus aligned via the photoalignment technique, structured by selective polymerization and attached to the substrate via the stamp-and-stick technique, and the overall angle made by both the flaps is tracked when the illumination is turned on and off.

Figure 5(b) shows the obtained bending response by the flaps with an irradiation of $81\ \text{mW cm}^{-2}$, leading to rise and fall times of 7 s and 19 s, respectively. The rise and fall

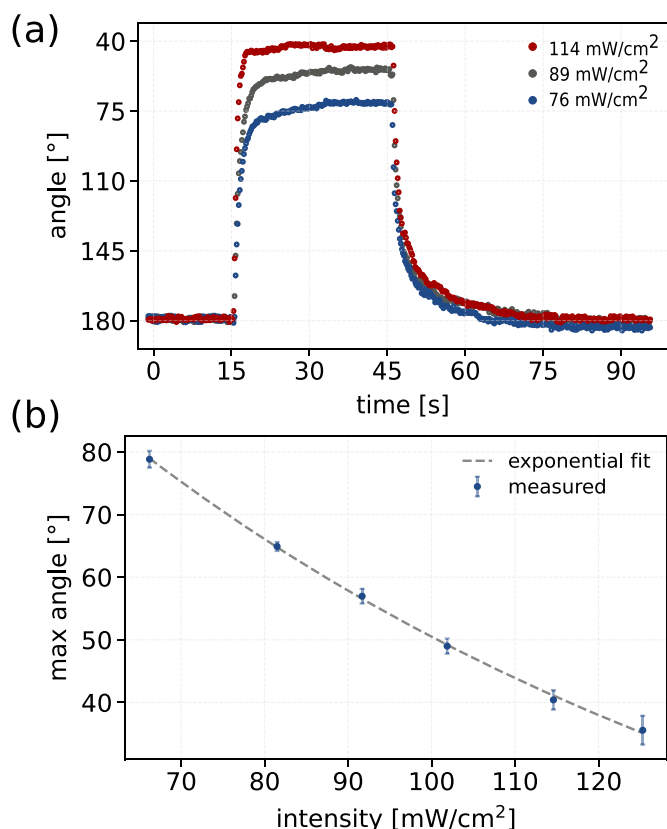


Figure 6. (a) The transient step response of the bending angle at different power intensities for one actuation cycle. (b) Maximum bending angle when actuator is illuminated at different power intensities with 450 nm. The error bars correspond to the sample standard deviation of three actuation cycles.

times are measured from the maximum bending angle for values from 10% and 90%. Due to the 60 μm thickness of actuator, which is higher in comparison to other published works [33, 44, 46], any heat generated during actuation will take extra time to dissipate in its surrounding environment, resulting in higher fall times of 19 s.

To further analyze the response behavior as a function of input intensities, three different input optical powers are applied in a step response. The obtained results are summarized in figure 6(a) where for different input optical powers, different targeted angles within $t_{\text{rise}} \approx 6$ s can be reached.

Furthermore, figure 6(b) demonstrates that the actuator can be held at different bending states by irradiating with constant input intensity. For measurements in figure 6(b), input power is applied as a step function and the maximum bending angle is recorded at $t = 40$ s. This recorded value is then plotted here as a function of input power.

3.2.2. Photochemical actuation. Figure 4(b1) illustrates the pattern for alignment and as well as for selective polymerization for photochemically induced actuation motion. This actuator is also 60 μm thick and is aligned in a 90° twist-bend fashion. As previously mentioned, upon illumination with 365 nm at 15 mW cm⁻² (figure 4(b3)), the globular shape of *cis*-azobenzene crosslinker disrupts the order of the network,

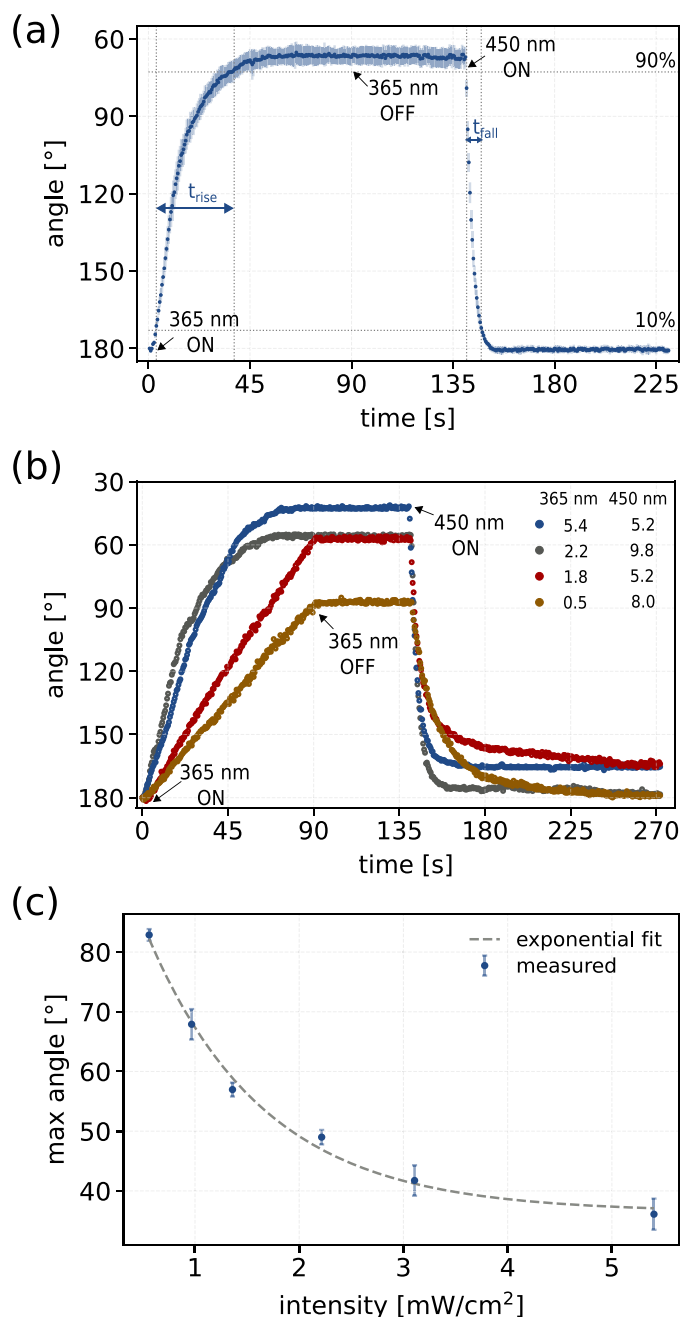


Figure 7. (a) The transient step response of photochemically driven LCN actuator with 0.2 mW cm⁻² irradiation of 365 nm and 1.01 mW cm⁻² irradiation of 450 nm. Each data point corresponds to the average value of ten actuation cycles and the corresponding error bars represents sample standard deviation ($n = 10$). (b) The transient step response of the bending angle at different power intensities for one actuation cycle. Values in the legend corresponds to illumination intensities of 365 nm and 450 nm LEDs in mW cm⁻². (c) Achievable maximum bending angles with the actuator when illuminated at different power intensities with 365 nm LED. The error bars correspond to the sample standard deviation ($n = 3$).

leading to actuation of the LCN. Since the half-lifetime of *cis*-azobenzenes used in this work is in the order of hours [33], reverse actuation motion takes place only after illuminating

the actuator with 450 nm at 55 mW cm^{-2} (figure 4(b4)), and is achieved in about 5 s.

Similar to the bending characterization for photothermal induced actuation, figure 7 summarizes the bending characteristics for photochemical induced actuation. A $60\text{ }\mu\text{m}$ thick film was attached to the substrate and the movement of the actuator was tracked in the similar fashion as illustrated in figure 5(a). When the actuator is illuminated with 1.2 mW cm^{-2} at 365 nm , it regains its maximum bending position within $\approx 45\text{ s}$. As soon as 450 nm LED with 9.8 mW cm^{-2} is turned on at $t = 140\text{ s}$, 10% of maximum value is achieved within 7 s.

Figure 7(b) summarizes the transient step response when different power intensities are applied as input to the actuator. Interestingly, the transient step response behavior of the actuator is dependent on the input intensity, unlike the response of photothermally driven actuators. At lower 365 nm intensities, the rise time behavior follows a steady linear increase, followed by constant actuated state when 365 nm LED is switched off. Increasing the intensity leads to shorter response times and higher bending angles. The fall response is also dependent on the intensity of 450 nm LED. At lower intensities, the original state of the actuator is not reached and the actuator position saturates after reaching a certain value.

Similar to figures 6(b) and 7(c) shows that the actuator can be held at different bending states depending on the intensity of 365 nm wavelength. For these measurements as well, input intensity is applied as a step response and the bending angle is recorded at $t = 120\text{ s}$.

For both actuator types just considered, the actuation response can be easily tuned by changing the length/width ratio and thickness [44, 46]; by changing the chemical system [21, 47]; or by simply increasing the input optical intensity [45].

3.2.3. Reproducibility. All the measurements summarized in figures 5–7 were performed at room temperature on a single photothermal or photochemical LCN actuator, each having a width of 5 mm and a thickness $60\text{ }\mu\text{m}$. The measurements on a single actuator were repeated for up to a total of 28 actuation cycles each, proving the stability of this soft-matter based actuator. In addition to this, the tight distribution of the bending characteristics as seen by the error bars, which correspond to the sample standard deviation in the figures 5 and 7, demonstrates the repeatability of obtained actuation characteristics from the actuator. Furthermore, any fluctuations in the measurements can be decreased by encapsulating the actuator in a housing, such that any influence of air flow is decreased.

4. Conclusions

We have demonstrated techniques to fabricate LCN actuators compatible with MEMS technology. Photoalignment of the LCs with BY allows creation of complex actuation profiles and structuring of these actuators is accomplished by highly-flexible maskless photolithography. Both the demonstrated techniques are performed with a DMD-based optomechanical

setup, hence simplifying the fabrication processes for these soft-matter-based actuators for MEMS devices.

With maskless photolithography technique, it is possible to structure $100\text{ }\mu\text{m}$ thick actuators in any arbitrary pattern with a resolution in the range of $1\text{--}2\text{ }\mu\text{m}$ to achieve a final actuation profile without any physical masks such as photoresists or stencils. It is possible to increase the structuring resolution by modifying the optomechanical setup to decrease the projected pixel size, either by using stronger demagnifying projection optics with appropriate numerical apertures or by using DMD with a smaller pixel pitch.

Furthermore, we have also quantified the structuring parameters of actuators with different chemical compositions having different actuator thicknesses. Since the optical system is optimized to work at different wavelengths, it is possible to structure the actuators with any wavelength from UVA–visible regime. This capability to work with different wavelengths provides another advantage over structuring techniques such as two-photon polymerization.

Additionally, we also reported on mechanical performance of the actuators, wherein different actuator states could be obtained depending on the input light intensity. The demonstrated performance of the actuators should serve as encouragement for further development and investigation of the integration of LCN actuators with MEMS devices.

Conflicts of interest

There are no conflicts to declare.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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