Reprogrammable 3D Liquid-Crystalline Actuators with Precisely Controllable Stepwise Actuation

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Liquid-crystalline elastomers (LCEs) are considered ideal soft actuator materials for a wide range of applications, especially the thriving soft robotics. However, 3D LCE actuators capable of precisely controllable stepwise actuation, which can enhance functionality and versatility of LCE robots for multifarious complicated applications, are still in urgent need for the reported LCE actuators mainly exploit the one-step actuation upon the liquid-crystallin (LC)-isotropic phase transition temperature ($T_i$). Herein, a catalyst-free LC-vitrimer actuator with supercritical behavior is designed, which can perform precisely controllable stepwise actuation with extraordinary shape stability over a broad temperature range of about 70 °C. Moreover, supercritical behavior enables the actuator to be used in nematic phase, imparting the actuator with some extra advantages, such as higher mechanical strength and actuation stability, over the one used above $T_i$. Furthermore, the LCE can be reprogrammable into arbitrary 3D actuators, which can further be integrated into single-material actuators with complex stepwise actuation, offering a generalized strategy of LCE actuators for sophisticated practical soft robots.

1. Introduction

Facing the demographic trends of aging populations and (often) negative population growth world around, robots will undoubtedly play an essential role to solve the issue of insufficient labor force in the future economic development and meet requirements for a high living standard as well. Soft robots, a nascent and rapidly growing area in robotics, are composed of soft deformable elastomeric materials to mimic human- or animal-like functions and can supplement, extend, and provide new functionalities that conventional stiff robots cannot realize. Due to advantages such as safe human–machine interaction, adaptation to unpredictable or dangerous environments, high degrees of motion freedom, and high specific power, soft robots have shown great potential in advanced high-tech fields from micromechanical systems, to military, biomedicine, rehabilitation and assistive technology.

Among numerous soft smart materials, liquid-crystalline elastomers (LCEs) stand out as soft actuator materials for soft robots due to their unique high-speed macroscopic reversible, complicated, and flexible deformability. As with LCEs, generally, complex spatial deformation can be achieved via 3D structures with mesogen alignment in different dimensions and directions. Thanks to the blooming development of novel LC-vitrimers, covalently crosslinked LCE networks that are able to be repeatedly reprocessed/reprogrammed via associative exchange reactions, LCE actuators with complex 3D geometries and diverse mechanical motions (such as bending– unbending, winding– unwinding, rolling, walking, and gripping–releasing motions) have been easily fabricated from 2D flat samples. To enhance functionality and versatility of LC-vitrimer robots in future sophisticated, dexterous, and high-level applications, actuators capable of precisely controllable stepwise actuation are of great importance. Previously, multimaterial permanently crosslinked LCE robots that integrate a variety types of LCE actuators with distinctive properties to realize stepwise actuation have been reported. However, this strategy will increase the fabrication difficulty/cost and the number of actuation steps is limited to the number of materials involved. In addition, once the aforementioned LCE actuators are fabricated, not any modification can be made for the permanently crosslinked networks. It is of great significance if one single LC-vitrimer actuator can perform 3D stepwise actuation at various temperatures, and thus assembled single-material actuators capable of complex 3D stepwise actuation can be conveniently fabricated. Meanwhile, by independently controlling actuating conditions of each part, functionality and versatility of the assembled actuators can be further enhanced. LC-vitrimer actuators can be repeatedly reprogrammed, which enables the modification of prior unsuitable actuators to function properly or the repurpose of actuators.
without disposal, saving much cost in new actuator preparation. However, to our knowledge, the reported LC-vitrimer actuators exploit only one-step actuation related to the ordered (LC phase) and disordered state (isotropic phase) transition.\(^6\)

Supercritical behavior of both traditional side-chain and main-chain nematic LCEs have long been investigated and discussed in literatures, that is a slow evolution of strain (i.e., continuous elongation/contraction behaviors) over the broad nematic range with temperature decreasing/increasing, other than a first-order transition caused fast on-off length change at the vicinity of nematic-isotropic phase transition within a narrow temperature range.\(^7\) Thus, continuous stepwise actuation can be easily realized as long as the LCE actuators possess supercritical behavior. However, for the previously reported supercritical LCEs, only simple 2D flat actuators were reported due to the difficulty in 3D actuator fabrication using permanently crosslinked networks. In the novel field of LC-vitrimers, whereas a few systems may have shown the supercritical phenomenon,\(^4h\) this fascinating supercritical behavior has been neglected and not been carefully studied nor purposely exploited for precisely controllable stepwise actuation yet.

Herein, we revisit supercritical behavior of nematic LCEs and extend it into a catalyst-free transesterification-based LC-vitrimer system to realize 3D actuators with precisely controllable stepwise actuation. Monodomain actuators with large reversible elongation actuation strain (75–80%) can be easily obtained by postaligning method as the literatures reported.\(^1c–i\) Due to the supercritical behavior, the actuators can undergo continuous stepwise actuation with temperature change over a broad temperature range up to 70 °C, even at a temperature interval of 2 °C. Furthermore, the shape at a given temperature is remarkably stable, yielding not any change during 5 h. Thus, the actuators can be utilized for precisely temperature-controllable mechanical works. Meanwhile, the actuators possess enough large actuation deformation within the nematic phase to meet the requirements for many applications, imparting which with some extra advantages such as improved mechanical strength and actuation durability compared with the ones being used above \(T_i\). Moreover, due to the reprocessability of vitrimers and supercritical behavior, precisely temperature-controllable 3D actuators (such as dome-shaped actuator and helical actuator) with stepwise actuation were directly fabricated from 2D samples. Furthermore, by welding assembly of 3D actuators with different shapes, functionalities, and motions, single-material soft actuators capable of thermal- or solar light-activated complex stepwise actuation were easily obtained.

### 2. Results and Discussion

#### 2.1. Synthesis and Basic Characterizations of the LCEs

The LCEs are synthesized using a modified method from the common-used two-step reactions of aza-Michael addition and photopolymerization between a nematic mesogens and primary amine\(^8\) through the following two procedures (Figure 1a).

1) Preparation of diacrylate end-capped liquid-crystalline oligomers (LCOs). LCOs are synthesized via aza-Michael addition between nematic monomer (1,4-bis-[4-(3-acryloyloxypropyloxy) benzoyloxy]-2-methylbenzene, RM 257) and chain extender (n-butylamine, n-BA) (preparation details can be found in Experimental Section). The end-capped diacrylate groups are obtained by employing RM 257 in molar excess to n-BA, with molar excess of 10%, 15%, and 20% (the corresponding oligomers obtained defined as LCO-10%, LCO-15%, and LCO-20%, respectively). By varying the ratio of diacrylate to amine, the average molecular weights of the LCOs are controlled, which decreases with the molar excess increasing (the details can be found in Experimental Section).

#### Figure 1

- **(a)** Synthesis and components of the LCEs. **(b)** An illustration of the catalyst-free transesterification. **(c)** Normalized shear stress relaxation of LCE-15% at varying temperatures. **(d)** Arrhenius plot of the measured relaxation time for LCE-15%. **(e)** Dilatometry curves of the three LCE samples.
found in the Figure S1, Supporting Information).

2) Photopolymerization of end-capped acrylate groups of LCOs, resulting in the crosslinked LCEs (defined as LCE-10%, LCE-15%, and LCE-20%, respectively. Preparation details can be found in Experimental Section). Swelling experiments for the three types of LCEs were conducted and the corresponding gel fraction (%) of average of three parallel samples, the details can be found in the Supporting Information) is about 88.4%, 92.7%, and 95.4%, verifying sufficient crosslinking in all the LCEs. Fourier transform infrared spectra (FTIR) clearly show that the characteristic peaks of terminal amine (3369 and 3291 cm⁻¹) have disappeared in LCOs and the end-capped acrylate groups of LCOs (810 cm⁻¹) have vanished after photopolymerization, confirming the completion of the curing reactions (Figure S2, Supporting Information).

### 2.2. Catalyst-Free Transesterification Behaviors

Before discussing the supercritical behavior of this LCE system, we will first illuminate another excited feature of this LCE, which is the catalyst-free transesterification behaviors. As is known, most of the reported LC-vitrimer systems need certain catalysts to activate the exchange reactions,[4a–6,9,10] which may give rise to the risk of toxicity, degradation, and leakage of catalysts during service time. Tertiary amines are one of the typical catalysts used to accelerate the exchange reactions in transesterification-based vitrimer. As with this LCE system, since a great number of alkaline tertiary amino groups generated in situ and covalently bonded to main-chains of the LCEs, they can active the transesterification reactions generated in situ and covalently bonded to main-chains of the LCEs, they can activate the transesterification reactions generated in situ and covalently bonded to main-chains of the LCEs. Fourier transform infrared spectra (FTIR) clearly show that the characteristic peaks of terminal amine (3369 and 3291 cm⁻¹) have disappeared in LCOs and the end-capped acrylate groups of LCOs (810 cm⁻¹) have vanished after photopolymerization, confirming the completion of the curing reactions (Figure S2, Supporting Information).

### 2.3. Monodomain LCE Actuator Fabrication

Due to the transesterification reactions, the mesogens can be aligned along the director of external force at elevated temperature, obtaining monodomain LCE actuators. It is found that heating at 160 °C for 5 min with a constant strain of 60% is suitable for the monodomain alignment of this LCE system (including LCE-10%, LCE-15%, and LCE-20%, the detailed alignment method can be found in the Figure S6, Supporting Information). The monodomain alignment was confirmed via 2D X-ray diffraction (XRD). Figure 2a shows the XRD images of the polydomain and monodomain LCE-15% films, where the arrow indicates the alignment direction. The 2D X-ray image of the polydomain film shows two rings, revealing no alignment of mesogens. On the contrary, the 2D X-ray image of the aligned film shows arcs wide-angle X-ray scattering (WAXS) pattern and four-spot small-angle X-ray scattering (SAXS) pattern. Moreover, 1D XRD curves of both the polydomain and monodomain LCE-15% show very weak diffraction peaks in the small-angle region. The aforementioned 1D and 2D XRD curves reveal a smectic (Sm) C-like cybotactic nematic phase (short-range Sm-like ordering in the form of nanometer-sized clusters, i.e., cybotactic groups) of the LCE system and the mesogen-order parameter S was calculated to be 0.62 (the detailed calculation method can be found in the Supporting Information).

Thus, on heating, the aligned LCE-15% can spontaneously contract when the LC-isotropic phase transition takes place, and reaches its equilibrium state above ≈95 °C as the transition into the isotropic state is completed. The phase transition temperatures of LCE-15% were measured by the differential scanning calorimetry (DSC), where the glass transition temperature (Tg) and LC-isotropic phase transition temperature (Tc) on heating were about 13 and 85 °C, respectively (Figure S3, Supporting Information). On the subsequent cooling, the sample starts to spontaneously elongate when it transforms to LC phase again. The spontaneous actuation behaviors of the three types of LCE samples were investigated using dynamic thermomechanical analysis (DMA). As shown in Figure 2b, the actuation strain decreases with the molar excess increasing. Considering both
actuation strain and mechanical strength, we chose LCE-15% in the rest parts to fabricate LCE actuators. The elongation actuation strain (taking the length at 95 °C as the initial length) of the monodomain LCE-15% actuators is about 75–80% (test on DMA) along the stretching direction. Moreover, the reversible actuation of the actuator can be successfully repeated for more than 1000 heating–cooling cycles (Figure 2c), revealing excellent actuation durability of the LCE actuator.

2.4. Supercritical Behavior of 2D LCE Actuators for Precisely Controllable Stepwise Actuation

Another intriguing feature of the LCE actuator here is the supercritical behavior, which is the continuous length change within the broad nematic phase except for a fast length change at the vicinity of nematic-isotropic phase transition within a narrow temperature range. An isostress (5 kPa) test was first conducted on the actuator by DMA to verify the supercritical behavior. The actuator was subjected to a continuous temperature increasing and decreasing cycle (0–105 °C, with a temperature interval of 5 °C) and held at each given temperature for 60 min (only for the main actuation temperature range 40–90 °C to shorten experiment time, held at the rest of temperatures for 20 min). As shown in Figure 3a, on cooling, the actuator begins to spontaneously elongate at temperature below 95 °C and reaches its longest length until 25 °C. Similarly, on heating, it begins to spontaneously contract at temperature above 25 °C and reaches its shortest length until 95 °C. The aforementioned results indicate that the monodomain actuators undergo stepwise length change over a broad temperature range up to 70 °C. Moreover, the actuation strain at each given temperature shows remarkable stability, of which the standard deviations (calculated from the last third of the data at each given temperature) are close to 0% and no more than 0.5% (Figure S9, Supporting Information). Moreover, the actuation strains can be precisely controlled and flexibly tuned by changing the temperature intervals. As is shown in Figure 3b, the actuator was successively subjected to temperature decreasing (105–0 °C) intervals of 2, 5, and 7 °C and held at each given temperature for 30 min. It reveals that even at a 2 °C temperature interval, the actuation strain still maintains excellent stability at a given temperature.

The precisely controllable stepwise actuating property was further confirmed by 5 °C stepwise heating and cooling the free-standing monodomain sample on a precise hot stage (30–100 °C). The length of the actuator at each given temperature was accurately measured after held for 5 min. As shown in Figure 3c, the actuator behaves very analogous to the sample tested on DMA, showing actuation at temperature range of 30–95 °C (we only show pictures of a 10 °C temperature interval here). It should be noted that this temperature range is a little different with the result of the isostress test by DMA, where the actuator deforms from 25 °C, for the hot stage used unable to be cooled to 25 °C and the actuation strain below 30 °C is very small and negligible. Moreover, the actuation strain at a given temperature is nearly the same on heating and cooling procedures, revealing excellent repeatability of the precisely controllable stepwise actuation of the LCE actuator (Figure 3d). The stability of the actuation strain was further verified by holding the actuator at a given temperature (such as 55, 65, and 75 °C) for 5 h, the length of which was accurately measured every hour.
As shown in Figure 3e, the length maintains almost unchanged during the 5 h experimental period.

The precisely controllable stepwise actuation of the LCE actuator can be applied for controllable weight lifting. As a demonstration, the actuator (with a weight of about 39.5 mg and a length of about 53.6 mm) was loaded with a metal clip of about 2744 mg (Figure 3f). When given a 5 °C stepwise temperature increasing and held at each given temperature for 5 min, the actuator contracted and lifted the metal clip up stepwise, indicating that the actuator can be utilized for precisely temperature-controllable mechanical works. Displacement and specific work of the actuators loaded with different weights were also investigated. As shown in Figure 3g,h, the displacement decreases, whereas the specific work increases (with a maximum energy density of 46.0 J kg⁻¹, the detailed calculation method can be found in the Supporting Information) with weight increasing in the experimental weight range (stress range 16–194 kPa). It should be noted that displacement is calculated using the unloaded length of the actuator as the initial length, rather than the elongated length when loaded, which is the reason for the negative displacement of higher weight (106 and 194 kPa) at lower temperature.

2.5. Extra Advantages that Supercritical Behavior Imparts with the LCE Actuators

In addition to the precisely controllable stepwise actuation, supercritical behavior imparts the LCE actuators with some extra advantages. First of all, supercritical behavior enhances the versatility of the actuators in various applications. As shown in Figure 4a, the
monodomain actuator shows different actuation strains (here, we used the contraction strain, that is taking the length at 0 °C as the initial length, which is the reason why the actuation strain is different from that the value of 75–80% calculated earlier and is negative) when heated to a series of temperatures and all cooled to 0 °C. This temperature-controllable precise actuation enable the actuator be used in multifarious tasks with different requirements for actuation behaviors, needless of new actuator fabrication for every new task. Second, as is known, LC-vitrimer actuators suffer from service stability/durability due to the activated exchange reactions at elevated temperatures to lose monodomain alignment.\[^{4g,i,j}\] Thanks to the supercritical behavior, the LCE actuator can work within the broad nematic phase. In a previous study, Terentjev’s group have testified that no any alignment would lose deep in the nematic phase even for the LC-vitrimer system with fast boronic-ester exchange reactions (processable in nematic phase) because the returning traction of the permanent network can be compensated by the extended chain configuration.\[^{4h}\] It is shown in Figure 4a that the actuation strain is about –21% (more than half of the whole actuation strain) in the nematic phase (below ≈80 °C), which is large enough to meet many applications. We further investigated the service stability of the actuator used in nematic phase. An actuator was subjected to spontaneous actuation cycles (heating–cooling between 75 and 0 °C) by DMA before and after heated at 75 °C for 120 h in an oven. As shown in Figure 4b, nearly no decrease occurs in the actuation strain, revealing outstanding actuation stability of the actuator in nematic phase. As a contrast, the actuation strain of the actuator cycled between 105 and 0 °C gradually declined by almost 3% within the first 100 actuation cycles (approximate to be heated at 105 °C for about 16.7 h, Figure 4c). It should be clarified that using in nematic phase can indeed improve the actuation stability and prolong the service life of the actuator but it is not to say that the actuator has very poor stability when used above \(T_i\) for it takes only seconds to finish an actuation cycles in practical applications, the stability of which has been proved in Figure 2c. Third, the actuator used in nematic phase also possesses more excellent mechanical strength than the one used above \(T_i\). The stress–strain data of monodomain LCE actuators at different temperatures (25–105 °C, with a 10 °C temperature interval) are shown in Figure S10a, Supporting Information, from which the corresponding elastic modulus and breaking strength were calculated. As shown in Figure S10b, Supporting Information, both the elastic modulus and breaking strength decrease with temperature increasing. For an instance, the elastic moduli of the actuators at 25, 75, and 105 °C were 4.4, 0.71, and 0.41 MPa, respectively, of which the corresponding breaking strengths were 6.31, 1.13, and 0.31 MPa. All the above results show the superior advantages of the LC-vitrimer actuator here with supercritical behavior over the previously reported one-step actuation LC-vitrimer actuators.

**2.6. 3D Actuators Capable of Precisely Controllable Stepwise Actuation**

Moreover, due to the transesterification reaction at elevated temperature and supercritical behavior, the LCE can be directly reconfigured into robust 3D actuators with mesogens well-aligned and the shapes of the 3D actuators can be precisely controlled with temperature varying. As a demonstration, we reconfigured the LCE film into a dome-shaped actuator (the detailed fabrication process can be found in the Supporting
Information), which is of great potentials in the tactile display field such as Braille displays. Unlike the reported similar actuators with only one-step change of height, the dome-shaped actuator can perform a precisely controllable stepwise height changing or realize required height by temperature controlling, which can greatly rich the pattern changes of thus devices. As shown in Figure 5a, the initial height of the dome-shaped actuator is about 3.85 mm at 35 °C. As temperature stepwise goes up, the height of the actuator decreases while maintains excellent stability at each given temperature. The actuator reaches its lowest height at temperature higher than 95 °C (with a height of 1.8 mm), which is resulted from permanent plastic deformation during aligning the mesogens at elevated temperature.

More complexed 3D actuators can also be fabricated. A helical actuator was readily fabricated by reconfiguration of the flat LCE strip (the detailed fabrication process can be found in the Supporting Information). The helical actuator also possesses the property of precisely controllable stepwise actuation over a broad temperature range. As shown in Figure 5b, with temperature stepwise increasing, the actuator shows a gradual unwinding deformation (with the cross-sectional area of the film increases, the length of the helical actuator decreases, the number of active coils decreases and helical diameter increases).

2.7. Assembled Complex Single-Material Soft Actuators via Welding of Separated 3D Actuators

Furthermore, utilizing welding strategy, the precisely controllable stepwise actuating 3D actuators with different shapes, functionalities, and motions can be conveniently assembled into complex single-material soft actuators for complicated practical applications. It has been proved that printed inks on the surface of polymer sheets can absorb light and convert it into heat\(^{[46,12]}\) and photothermal welding has great advantages over direct-heating welding, especially for monodomain LC-vitrimer actuators.\(^{[46]}\) Here, for simplicity, we used the commercial permanent markers as printed inks. As shown in Figure 6a, four different 3D actuators with local black ink coating (left-handed helix with the similar pitch, helicoid, right-handed helix with the changing pitch, and right-handed helix with the similar pitch, which were labeled as Actuator-1, Actuator-2, Actuator-3, and Actuator-4, respectively) were joined together via photothermal welding (808 nm NIR light, the details of four actuators fabrication and welding assembly can be found in the Supporting Information). As shown in Figure 6b, with temperature stepwise increasing, each part of the assembled soft actuator (labeled as TA-SSA, thermal-activated assembled soft actuator) can perform distinctive stepwise actuating behaviors over a broad temperature range, imparting the soft actuator with multiple deformations in different areas, dimensions, and directions. The complicated stepwise actuation of the TA-SSA makes it a versatile actuator for different tasks, dispensing with the fabrication of new actuators for every new work. To further enhance the multifunctionality and versatility of the TA-SSA, printed inks (black ink, blue ink and red ink) with different photothermal effects were individually painted on both sides of Actuator-1, Actuator-2, and Actuator-3 of the above TA-SSA, where the painted actuators were labeled as Actuator-1', Actuator-2', and Actuator-3', respectively, and Actuator-4 maintained unpainted (the actuator obtained was labeled as LA-SSA, light-activated assembled soft actuator, Figure 6c). Photothermal effect investigations via an infrared

Figure 5. Precisely controllable stepwise actuation of the a) 3D dome shaped and b) helical LCE actuators (the top is the schematic illustration of shape change).
thermal imager show that the four actuators possess different photothermal conversion capabilities at the same solar light intensity, and temperatures of the four actuators always follow the relationship $T_1 > T_2 > T_3 > T_4$ under various solar light intensities (the details can be found in the Figure S14b, Supporting Information), revealing obvious photothermal effect of the printed inks as well. Thus, when exposed to solar light of a given intensity, differing from the above TA-SSA, each part of the LA-SSA was heated to a different temperature. For instance, at light intensity of 0.32 W cm$^{-2}$, temperatures of the four actuator parts are about 85.3, 74.4, 67.5, and 51.4 °C, respectively. As shown in Figure 6d, when irradiated with stepwise increasing light intensities, Actuator-1', Actuator-2', Actuator-3', and Actuator-4 start their stepwise deformations in sequence, which will greatly enlarge the deformation temperature range and deformation diversity of the LA-SSA compared with the TA-SSA. It should be noted that all parts of the actuators here is exposed to the same external controlling conditions. In further practical applications, more numbers of actuator parts can be involved and each part of the actuator can be independently controlled, enabling unlimited numbers of deformations be realized within the same SSA.

3. Conclusion

In summary, a main-chain LC-vitrimer system with supercritical behavior was synthesized, which enables precisely controllable stepwise actuation over a broad temperature range. First, the great number of alkaline tertiary amino groups endows the LCE system with catalyst-free transesterification effect at elevated temperature, endowing the LCE with excellent reprocessability such as post-aligning and reconfiguration. Second, the shape of the monodomain LCE at a given temperature can be precisely controlled with outstanding stability. Third, the large actuation deformation within nematic phase enables the actuators to be used in nematic phase to eliminate the risk of alignment loss when they work in isotropic phase. Fourth, the actuator used in nematic phase also possesses more excellent mechanical strength than the one used above $T_N$. Moreover, due to the reprocessability and supercritical behavior, 3D actuators capable of precisely controllable stepwise actuation were successfully fabricated. Furthermore, assembled single-material soft actuators capable of thermal- or solar light-activated complex stepwise actuation were easily obtained by welding assembly of 3D actuators with different shapes, functionalities, and motions, which greatly simplifies the fabrication, enhances functionality and versatility of LCE actuators in various complicated applications. The strategy introduced here is not limited to the current system. Based on this strategy, other supercritical LC-vitrimer actuators with different thermomechanical response or mechanical properties can be easily fabricated into assembled single-material soft actuators. We hope this work would be a generalized strategy of designing LCE actuators for various sophisticated practical applications.

4. Experimental Section

Materials: 1,4-Bis-[4-(3-acyloyloxypropyloxy) benzoyloxy]-2-methylbenzene (RM 257, 98%) was purchased from Sdynano Fine Chemicals in Shijiazhuang. Irgacure-651 (I 651, 98%), n-butylamine (n-BA, 99.5%) were
obtained from J&K. Dichloromethane (AR) and tetrahydrofuran (AR) were purchased from Tongguang Fine Chemicals in Beijing. All the reagents were used directly without further purification.

Synthesis of the LCOs: RM 257 and chain-extender (n-BA) with required ratio of diacrylate:amine (1.10:1, 1.15:1, and 1.20:1, respectively) were individually added into 2 mL centrifuge tubes. The mixtures were heated with stirring at 85 °C for 20 h, during which, the acrylate and amine groups underwent chain extension via aza-Michael step-growth addition reactions, resulting in LCO-10%, LCO-15%, and LCO-20%, respectively.

Synthesis of LCEs: The aforementioned as-prepared three types of LCOs (0.4 g) and the photoinitiator I 651 (3 wt% of the total LCOs) were added to dissolve the mixtures with ultrasound dispersion. Then the viscous mixtures were transferred into home-made quartz glass molds (assembling two pieces of quartz glass separated by a 400 μm spacer), followed by being exposed to UV light (λ = 365 nm, 40 mW cm⁻² and 20 min for each side) at room temperature for photopolymerization of the acrylate groups. After photopolymerization, the obtained LCE-10%, LCE-15%, and LCE-20% were dried in vacuum oven at 60 °C for 24 h.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Y.J. and Q.C. developed the concept. Y.J., Q.C., and Y.W. arranged the funding and infrastructure for the project. Q.C. carried out the experiments. Q.C. and Y.J. wrote the article. All of the authors contributed to scientific discussion of the article.

Data Availability Statement

Research data are not shared.

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