Biconvex polymer microlenses fabricated from microfluidic Janus droplets*

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We present a microfluidic platform for high-throughput moldless fabrication of biconvex polymer microlenses. Using a confined sheath-flowing geometry that is dry-etched on a glass chip, we produced compound droplets composed of a photocurable acrylate monomer and a non-curable silicone oil containing a surfactant. The droplets developed reproducibly and rapidly in a co-flowing aqueous stream (e.g., at ~200 drops/s). At equilibrium, the produced compound droplets formed a *Janus* geometry with photocurable segments having a biconvex shape, and they were monodispersed with coefficients of variation below 5%. Subsequent off-chip photopolymerization continuously yielded biconvex acrylic microlenses of uniform sizes and shapes. By varying the flow rates we could control the production rate and the size of the Janus droplets (equivalent diameter of 120–200 μm). In addition, the shape of the Janus segments and resultant particles could be tuned by varying the flow rate ratio of the two droplet phases as well as the type of surfactant dissolved in the non-curable phase. We also confirmed that the prepared biconvex microparticles could be used as optical lenses. With flexible size and shape control, low energy input, and the rapidity and scalability of the system, this technique has considerable potential as a manufacturing process for high-throughput microlens production.

Key words: microfluidics, Janus droplet, biconvex microlens, interfacial tension

1. Introduction

Microlenses are widely applicable in optical communication and signal processing systems, including CCD cameras, copying machines, and modules for fiber coupling and telecommunications. To date, a number of methods have been proposed for fabricating various microlenses. For example, moldless techniques including the thermal reflow method¹⁾, grayscale photolithography²⁾, laser fabrication³⁾ and micro jetting⁴⁾ have been reported for fabricating various polymeric and glass microlens arrays. However, these methods are limited to microlenses arrayed on a planar substrate, each with single lens curvature. Mold-assisted techniques which use 3D solid molds as template, including hot embossing⁵⁾ and injection molding⁶⁾, are suitable for creating microlenses with dual lens surfaces; these include biconvex, biconcave, and convex-concave lenses. These molding techniques are less expensive and more suitable for mass production in industry than moldless processes. However, mold-assisted techniques require a photolithographical process or high-precision mechanical machining to microfabricate a solid mold specific for a microlens of a desired shape. This makes it difficult later to flexibly change the shape of the lenses within a short time and at low cost.

The use of fluidic templates and interfacial energies has recently been reported for the fabrication of polymeric lens-shaped particles. Nakazawa et al.⁷⁾ produced biconvex polymeric particles of size ~

2mm by photopolymerizing resin droplets with biconvex shapes placed at the interface of water and n-hexane. More recently, microfluidic compound droplets have been used to prepare a higher throughput of lens-shaped polymeric particles with smaller sizes. Nisisako et al.^{8,9)} fabricated hemispherical and concave-convex acrylic particles with uniform shapes and sizes (~100 μm) via the rapid generation (e.g., 50–400 drops/s) of nanoliter-sized *Janus* droplets having photocurable and non-curable segments. A similar microfluidic technique using the evolution of droplets from the core-shell to the Janus state has been reported to engineer nonspherical particles^{10–12)}. Compared to mold-assisted methods such as hot embossing and injection molding, these moldless methods can potentially fabricate microlenses at significantly higher throughput and with lower energy input. However, no microfluidic method has been reported yet for the fabrication of biconvex micro particles.

Here, we report for the first time a high-throughput fabrication of biconvex polymer microlenses from microfluidic Janus droplets.

Fig. 1 Schematic illustrations of (a) a microfluidic Janus droplet generator and (b) off-chip photopolymerization process for making biconvex polymer microlenses

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Fig. 2 Interfacial free energies forming a Janus geometry. (a) Schematic illustration showing the balance of three liquid-liquid interfacial tensions on a Janus droplet. (b) Neumann triangle¹³⁾. (c) Phase diagram based on the three interfacial tensions showing where Janus and two other states can be obtained at equilibrium. The star symbol at (2.4, 2.0) denotes the condition used previously⁸⁾⁹⁾

Using a symmetric sheath-flowing geometry (**Fig. 1**), we produced Janus droplets of photocurable and non-curable segments; this occurred reproducibly and rapidly, for example, at a breakup rate of ~ 200 drops / s. The use of a surfactant-containing non-curable solution as the template droplet phase resulted in the photocurable segments of the produced droplets forming a biconvex shape at equilibrium. The subsequent off-chip continuous photopolymerization yielded biconvex particles of uniform sizes and shapes. We theoretically simulated the shape of the droplet segments and the resultant particles at various interfacial energies and volume ratios of the droplet phases. We could experimentally vary the shapes of the lenses by varying the volume ratios of the two droplet phases or by using a different surfactant in the template droplet phase. We also demonstrated that the prepared particles could work as optical biconvex lenses.

2. Theoretical model of a compound droplet

If a compound emulsion drop that has two segments is sufficiently small, then the body forces acting on the droplet are negligible compared to the surface forces. In this case, the shapes of the compound droplet and each segment are determined by two sets of parameters: the interfacial energies at three liquid-liquid interfaces and the volume ratio between the two droplet phases.

The three interfacial energies at three interfaces become involved when a compound droplet composed of phases 1 and 3 is dispersed in the external continuous phase 2: γ_{12} at the interface between phases 1 and 2; γ_{23} at the interface between phases 2 and 3; and γ_{31} at the interface between phases 1 and 3. Through the minimization

Fig. 3 Effect of the volume ratio between two droplet phases on the shape of the Janus segments. (a) Volume ratio vs. radii of curvature R_{31} and R_{23} (see inset) when $\gamma_{12} = \gamma_{23} = \gamma_{31}$. (b) Volume ratio vs. radii of curvature R_{23} and R_{31} when $\gamma_{12} = 5.3 \text{ mN m}^{-1}$, $\gamma_{23} = 4.5 \text{ mN m}^{-1}$, and $\gamma_{31} = 2.2 \text{ mN m}^{-1}$ (values from Refs. 8 and 9). R_{eq} is the equivalent radius of a Janus sphere, given by $R_{eq} = (3(V_1 + V_3) / (4\pi))^{1/3}$

of the interfacial free energy of the droplet at equilibrium, a compound droplet forms one of the following three structures: (1) complete engulfment, (2) partial engulfment (Janus), or (3) non-engulfment (two separate droplets). A Janus geometry (**Fig. 2a**) is formed when the three interfacial tensions are balanced, as shown in Neumann's triangle¹³⁾ (**Fig. 2b**).

The relation between a set of three interfacial energies and three droplet structures can be described by the spreading parameters: $S_i = \gamma_{jk} - (\gamma_{ij} + \gamma_{ki})$, where $i, j, k = 1, 2, 3$. When the indices 1 and 3 for two droplet phases are chosen to satisfy $\gamma_{12} > \gamma_{23}$, then S_1 is always negative and the conditions for the three droplet structures are described as follows: $S_1 < 0, S_2 < 0, S_3 > 0$ for complete engulfment; $S_1 < 0, S_2 < 0, S_3 < 0$ for Janus; and $S_1 < 0, S_2 > 0, S_3 < 0$ for non-engulfment. When $\gamma_{12} < \gamma_{23}$, the relations between the spreading parameters and the droplet structures can be similarly obtained. A phase diagram can be created from these relations (**Fig. 2c**), showing the interfacial energy conditions leading to each of the three droplet structures¹⁴⁾. From this diagram we can intuitively understand which conditions of interfacial energies are needed to produce Janus droplets and biconvex lenses. First, the interfacial energies of two droplet phases against the external continuous phase (i.e., γ_{12} and γ_{23}) should not differ significantly; otherwise the droplet forms a core-shell geometry. Second, the interfacial energy between two droplet phases (i.e., γ_{31}) should not be too large

compared to the other two elements; otherwise the two segments will separate into two distinct droplets. Also, we can understand that the balance of γ_{12} and γ_{23} determines which of the two droplet segments obtain a biconvex or convex-concave shape. Within this region of the Janus state, we can control the shape of the droplet segments and the subsequent lens-shaped particles by varying the interfacial tensions.

The size and curvature of the segments in a Janus droplet can be widely varied by changing the volume ratio between two droplet phases. **Figure 3a** shows the simulated relation between the volume ratio and the curvatures of the Janus segment when the three interfacial energies are equal. As shown in the graph, the radius of curvature at the interface of the two droplet phases (R_{31}) can vary widely, while the radius of curvature at the interface between a droplet phase and an external phase (R_{23}) is nearly constant. We also find that the concave-convex geometry can be switched by changing volume ratios. **Figure 3b** shows the effect of the volume ratio on the radii of curvature that the authors calculated with the actual values of the interfacial energies used for making hemispheres and concave-convex particles^{8,9)}. In this graph, phases 1 and 3 are the non-curable and photocurable segments, respectively. From this graph, we can understand that the biconvex photocurable segment (phase 3) can be obtained only at a low volume fraction of the curable phase ($V_3/(V_1+V_3) < 0.2$), and it is difficult to produce biconvex particles over a wide volume range.

Therefore, in this study, we added surfactant to non-curable phase (phase 1) to decrease γ_{12} and to realize $\gamma_{12} < \gamma_{23}$. This enabled us to form biconvex photocurable segments (phase 3) over a wide volume range.

3. Materials and methods

3.1. Microfabrication

A planar microfluidic geometry, comprising a Y-shaped channel and a sheath-flowing geometry, was prepared on a glass chip, using the deep reactive ion etching (DRIE) technique as described previously^{8,9)}. Around the droplet generator, the channel width was 100 μm for the input channels and the orifice and 200 μm for the drain channel with a uniform depth of 100 μm . The microfluidic channel with naturally hydrophilic surface was used without any surface modification.

3.2. Materials

The photocurable organic phase was 1,6-hexanediol diacrylate (HDDA, dynamic viscosity $\eta_m = 6.35$ mPa s, density $\rho_m = 1.02$ g cm^{-3} , Shin-Nakamura Kagaku, Tokyo, Japan). For subsequent polymerization, a photoinitiator (Darocur 1173, Ciba Japan K. K., Tokyo, Japan) was dissolved in the monomer so as to generate a 1.0 wt% mixture. For the non-curable organic phase, silicone oil (SH200 10CS, $\eta_s = 9.34$ mPa s, $\rho_s = 0.934$ g cm^{-3} , Dow Corning Toray, Tokyo, Japan) was used. Oil-soluble dye (Oil Blue N, Sigma-Aldrich, MO, USA) was dissolved in the monomer so as to differentiate the two organic phases visually. Two surfactants (BY11-030 and BY22-008M, Dow Corning Toray) were separately dissolved in the silicone oil to prepare 1wt% solutions. For the external aqueous phase, sodium dodecyl sulfate (SDS, Wako Pure Chemicals, Tokyo, Japan) was dissolved in pure water, to prepare

Fig. 4 A microfluidic device for generating Janus droplets

0.3 wt% solution ($\eta = 1.0$ mPa s). Viscosities of the liquids were measured at room temperature (293 K) using a rotational viscometer (B-type, Toki Sangyo, Tokyo, Japan). The interfacial tensions between the organic and aqueous phases were determined at room temperature (293 K) by a tensionmeter using the Wilhelmy plate method (CBVP-Z, Kyowa Interface Science, Saitama, Japan).

3.3. Microfluidic experiments

The glass microchip (12 mm $\times$ 12 mm $\times$ 3.5 mm) was assembled in a stainless steel holder, and was linked to syringes through poly(tetrafluoroethylene) (PTFE) tubes (0.5 mm internal diameter, 1.5 mm external diameter) (**Fig. 4**). Gastight glass microsyringes (1000 series; Hamilton Company, NV, USA) were filled with the liquids, and mounted on syringe pumps (KDS200, KD Scientific, PA, USA). Formation of Janus droplets in the microchannel was monitored by a high-speed video camera (Fastcam-1024PCI, Photron Limited, Tokyo, Japan) mounted on an upright microscope (BX-51, Olympus, Tokyo, Japan).

3.4. Preparation of polymer microlenses

The polymeric microparticles were continuously photopolymerized by a UV light source (LA-410UV, HAYASHI, Japan) at the end of the drain tube from the microfluidic module. The products were filtered using a nylon mesh (grid size 40 μm $\times$ 40 μm), to remove smaller particles made from satellite droplets. The particles were lightly washed using acetone and ethanol to remove the non-curable fluid.

3.5. Characterization of droplets and microlenses

Both the optical microscope and a scanning electron microscope (SEM, VE-8800, Keyence, Osaka, Japan) were used to obtain images of the droplets or particles for characterization. An image processing software (Image Pro, Media Cybernetics, U.S.A.) was used to measure the dimensions of the prepared droplets and particles. A free software, Surface Evolver¹⁵⁾, was used to simulate the effect of interfacial energies on the shape of compound droplets.

4. Results and discussion

We infused an acrylate monomer (HDDA) as the photocurable droplet phase, silicone oil (SO) containing a surfactant (BY11-030) as the non-curable droplet phase, and SDS aqueous solution as the external aqueous phase into the microfluidic droplet generator. When the flow rates of the droplet phases (Q_d in total) and

Fig. 5 Formation of Janus droplets having non-curable segments carrying surfactant. (a) Formation of Janus droplets with equal flow rates of curable (Q_m) and non-curable (Q_s) phases ($Q_m = Q_s = 0.25 \text{ mL h}^{-1}$). The flow rate of the continuous aqueous phase Q_c was 4.0 mL h^{-1} ($2.0 \text{ mL h}^{-1} \times 2$). (b) Janus droplets with dyed photocurable segments flowing through the drain tube (i.d. 0.5 mm). (c-f) Janus droplet formation at various flow rate ratios between two dispersed phases; (c) $Q_m:Q_s = 1:4$, (d) $2:3$, (e) $3:2$, (f) $4:1$. $Q_m + Q_s = 0.5 \text{ mL h}^{-1}$, $Q_c = 5.0 \text{ mL h}^{-1}$ ($2.5 \text{ mL h}^{-1} \times 2$)

surrounding aqueous phase (Q_c) were set appropriately in the range of a low Reynolds number and low capillary number, nanoliter-sized compound droplets of the two immiscible phases were reproducibly generated at the orifice (**Fig. 5a**). The droplets and the ligament in the captured image suggests that the interfacial energy at the SO/water interface is larger than that of the HDDDA/water interface, probably due to insufficient adsorption of the surfactants in the SO segment immediately prior to and after the droplet formation at the orifice. It was difficult to judge whether the compound droplets right after generation in the channel have a core-shell geometry or a Janus state. However, in the downstream drain tube, we find that all of the prepared compound droplets were flowing in a Janus state (**Fig. 5b**). We varied the volume ratio of the two droplet segments simply by varying the flow rate settings (**Figs. 5c-f**). These observations were similar to previous experiments without a surfactant in the non-curable droplet phase^{8,9)}.

Figure 6a shows a flow diagram of the conditions that lead to the formation of Janus droplets with surfactant. The region in which the Janus droplets can be formed was a closed mountain-like region in the range of low capillary numbers: $Ca = 10^{-3} - 10^{-2}$. This Ca range and the shape of the region are similar to those reported previously for the formation of surfactant-free Janus droplets^{8,9)}. When Q_d is too low, the two-phase organic stream becomes unstable, and no monodisperse Janus droplets are formed⁸⁾. When Q_d is too high, the two-phase organic stream is elongated toward the downstream of the drain channel, and Janus droplets cannot be formed. The maximum throughput of $Q_d \sim 1.3 \text{ mL h}^{-1}$ is close to the result in a sheath-flowing geometry with similar dimensions without surfactant⁸⁾. By changing Q_c and Q_d in this region, we are able to flexibly tune the breakup frequency in the range of $10\text{--}200 \text{ drops s}^{-1}$, as well as the size of the droplets in the range of $120\text{--}200 \text{ μm}$ (**Figs. 6b and 6c**). Overall, we did not observe any significant effect of the surfactant in the non-curable droplet phase on the hydrodynamic

Fig. 6 Hydrodynamic effects on the generation of Janus droplets. (a) A phase diagram showing where monodisperse Janus droplets can be formed. Ca is the capillary number, given by $Ca = \eta U \gamma^{-1}$, where $\eta = 1.0 \text{ mPa s}$, U is the averaged velocity of the continuous phase stream, and $\gamma = 8.1 \text{ mN m}^{-1}$. Open circles and solid squares represent conditions under which generation frequencies were measured, as shown in (b). (b) Measured relation between the continuous phase flow rate Q_c and the generation frequency F at a fixed dispersed phase flow rate $Q_d (= Q_m + Q_s, Q_m = Q_s)$. Fitted lines show $F \propto Q_c$. (c) Q_c vs. droplet size D_{eq} calculated from the frequency data in (b). D_{eq} is the equivalent diameter in a spherical shape, and D_h is the hydraulic diameter of the orifice of the droplet generator ($= 100 \text{ μm}$). Fitted lines show $D_{eq}/D_h \propto Q_c^{-1/3}$

phenomena near the droplet generator. This is probably because the absorption of the surfactant molecules at the fluid interface is sufficiently slow compared to the hydrodynamic breakup of the Janus droplets.

Before UV-curing experiments, we collected the produced droplets in an off-chip petri dish and observed them at surface-energy equilibrium by using optical microscopy. Since the compound droplets had a lower density than the surrounding aqueous phase and the water surface in the petri dish had a convex meniscus, the droplets floated and formed a densely packed two-dimensional array at the water-air interface (**Fig. 7a**). No coalescence was observed among the droplets for at least several minutes, suggesting that the SDS molecules in the external aqueous phase successfully stabilized the droplets. From a top view, each droplet was seen to consist of two concentric circles, and it was unclear whether the droplets had a core-shell or Janus geometry. However, we found that the satellite compound droplets ($\sim 20 \text{ μm}$), which were much smaller than the primary droplets, had a Janus configuration, and also the effect of the gravitational force was smaller (**Fig. 7b**). From these satellite droplets and the observation in the drain tube (**Fig. 5b**), we believe that the droplets in **Fig. 7a** have a Janus geometry, standing with a lighter non-curable SO phase up and heavier photocurable HDDDA phase down at the air-water interface. Next, using dyed HDDDA as photocurable phase, we confirmed that the inner circle of the droplets (**Fig. 7a**) corresponds to the photocurable segment (**Fig. 7c**). This suggests

Fig. 7 Janus droplets at equilibrium. (a) Main droplets having two segments of equal volume. (b) Satellite Janus droplets. (c) Janus droplets with dyed photocurable phase. (d) Schematic of a floating Janus droplet in (a) and (c). (e) The size distributions of Janus segments measured from the image in (a). (f) Main droplets with polydispersed HDDA segments produced at $Q_m/Q_s = 1/4$ (see Fig. 5c)

that the photocurable segment at the bottom has two convex surfaces, schematically shown in **Fig. 7d**. These Janus droplets had a narrow size distribution (D_1 and D_3 in **Fig. 7d**) with coefficient-of-variation (CV) values below 5 % (**Fig. 7e**).

We observed droplets having multiple polydispersed HDDA segments (**Fig. 7f**) when we produced droplets with the lower volume ratio of the photocurable phase. Such droplets were not observed in previous studies on surfactant-free Janus droplets^{8,9}. We consider two reasons for these polydispersed segments. First, we believe that thin HDDA segments in the compound droplets were easily broken by the shearing force in the channel, due to the low interfacial tension resulting from the surfactant in the non-curable phase. Furthermore, these polydispersed HDDA segments were stabilized by the surfactant and did not coalesce again. That is, the occurrence of these droplets suggests that the surfactant added to the non-curable phase worked. On the contrary, Janus droplets with two distinct segments could form when we created droplets with a higher volume ratio for the HDDA segments.

By off-chip photopolymerization, we polymerized the biconvex segments in the Janus droplets, yielding monodisperse biconvex acrylic particles (**Fig. 8a**). The prepared particles had two convex surfaces: one surface was from the HDDA/water interface and the other from the HDDA/SO interface. We identified these two surfaces because the convex surface from the HDDA/SO interface contained a small amount of debris, probably due to the slight mixture of HDDA and SO at the interface. Using image analysis, we measured radii of the two convex surfaces and thickness of the particles; we selected multiple particles showing their thickness appropriately in the optical microscopy images. Both of these surfaces were found to be spherical and their radii had narrow distributions (average radius 60.2 μm with a CV of 5% for R_{23} , and average radius 64.2 μm with a CV of 6.8% for R_{31} , **Fig. 8b**). The

Fig. 8 Characterization of the biconvex polymer microparticles. (a) A scanning electron microscopy (SEM) image of the biconvex particles. (b) Measured radii of two convex surfaces of the particles. (c) Volume ratios of the Janus segments vs. radii of the two convex surfaces

Fig. 9 Hemispherical particles molded by a non-curable segment containing the surfactant BY22-008M. Inset shows the Janus droplets at equilibrium before photopolymerization

thickness of these particles was also narrowly distributed, with an average of 108 μm and a CV of 2.7% ($n = 12$). We could vary these radii by varying the volume ratio of the HDDA phase in the droplets in the range of 0.4–0.8 (**Fig. 8c**). The shape uniformity of these particles might be further improved if UV light is irradiated more uniformly from all directions to the droplets.

When we used a non-curable phase having a different surfactant (BY22-008M), we significantly changed the shape of the Janus droplets and the resulting particles. We could generate Janus droplets similarly, but the resultant particles had a hemispherical shape, with a hemispherical surface and a flat surface (**Fig. 9**). This result meant that BY22-008M does not decrease the interfacial energy at the SO/water interface as much as BY11-030 does. This

Fig. 10 Optical property of the prepared biconvex microlenses. (a) Schematic illustration of the optical experimental setup (not to scale) and a photomicrograph of letters printed by a laser printer. (b,c) Observation target 'M' and an image through a biconvex lens, which is reduced by 1/13 and rotated by 180 degree. (d,e) Effect of distance variation between the lens and observation target. Magnified (d) and reduced (e) images through a biconvex lens

result suggests that we could tune the shape of the lenses by considering surfactant types and their concentrations.

We conducted a simple optical test to confirm if the prepared biconvex particles could work as an optical biconvex lens. We put the prepared biconvex particles on a transparent glass slide and observed small letters ($\sim 300 \mu\text{m}$) printed on paper through the particles using optical microscopy (**Figs. 10a and 10b**). The focal length f of a biconvex lens in air is given by the following equation:

$$\frac{1}{f} = (n-1) \times \left(\frac{1}{R_1} + \frac{1}{R_2} \right) - \left(\frac{d(n-1)^2}{nR_1R_2} \right) \quad (1)$$

where n is the refractive index of the lens medium, d is the thickness of the lens, and R_1 and R_2 are the radii of the lens curvature where light comes in and goes out, respectively. By incorporating $n = 1.456$, $R_1 = 60.2 \mu\text{m}$, $R_2 = 64.2 \mu\text{m}$ (or $R_1 = 64.2 \mu\text{m}$, $R_2 = 60.2 \mu\text{m}$), and $d = 108 \mu\text{m}$, we obtained $f = 93.6 \mu\text{m}$. Thus, the focal length was less than the thickness of the glass slide (1mm). Then we observed the letters that were placed beyond the focal length. Through the biconvex particle, we could observe the 180-degree rotated image (**Fig 10c**), which is typical for the observation of samples placed beyond the focal length through a biconvex lens. Also, by changing the distance between the paper and the biconvex lens, we could magnify or demagnify the size of the letters (**Figs. 10d and 10e**). Thus, we demonstrated that the prepared particles could be used as biconvex lenses.

Our method can be enhanced in multiple ways. For example,

much smaller biconvex lenses (e.g., as small as $10 \mu\text{m}$) could be readily prepared if a microfluidic channel with similar cross-sectional sizes is used. To use these smaller particles as individual lenses, however, an efficient handling technique is needed for assembly. In contrast, coating free surfaces with a large number of such microlenses would allow the preparation of functional objects covered by a microlens array. Larger lenses having millimeter scale could also be prepared via larger fluidic channels, although the channel and the droplets need to be small enough to minimize the distortion caused by gravitational force. Aspherical biconvex microlenses could be prepared if the polymerization process is conducted on distorted Janus droplets under physical constraint in the confined microfluidic channel. The functionalization of a specific lens surface would be possible by selective adsorption using hydrophilic/hydrophobic interaction¹⁶. In this study we used HDDA because it was rapidly photocurable; similar photocurable or thermo-curable fluidic materials would be also useful to make similar particles. It would be interesting to apply our technology to inorganic materials such as synthetic quartz glass. Production throughput could be easily scaled up via large-scale parallelization of microfluidic channels on a chip¹⁷.

5. Conclusion

We demonstrated high-throughput fabrication of biconvex polymeric microlenses using a microfluidic Janus droplet generator. The surfactant in the non-curable segment allowed us to form a biconvex curable segment, thereby producing biconvex polymer microlenses via off-chip photopolymerization. The shape of the lenses can be controlled by changing the volume ratios of the two droplet phases or the surfactants added to the template phase. The prepared biconvex particles can be used as optical lenses. We believe this technology has the potential for high-throughput fabrication of shape-controlled microlenses for numerous applications.

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