Lab on a Chip

View Online
Dynamic Article Links

Cite this: DOI: 10.1039/c0lc00706d

www.rsc.org/loc

PAPER

Faster multiple emulsification with drop splitting†

Adam R. Abate and David A. Weitz*

Received 18th December 2010, Accepted 14th March 2011
DOI: 10.1039/c0lc00706d

Microfluidic devices can form emulsions in which the drops have an intricate, controlled structure; however, a challenge is that the droplets are produced slowly, typically only a few millilitres per hour. Here, we present a simple technique to increase the production rate. Using a large drop maker, we produce large drops at a fast volumetric rate; by splitting these drops several times in a splitting array, we create drops of the desired small size. The advantage of this over forming the small drops directly using a small drop maker is that the drops can be formed at much faster rates. This can be applied to the production of single and multiple emulsions.

Introduction

Double emulsions are droplets that contain additional smaller drops inside.[1,2] Because of their small dimensions and core–shell structure, they are useful for applications requiring microencapsulation, including in foods, cosmetics, and pharmaceuticals.[3–5] With microfluidic devices, double emulsion drops can be formed with controlled properties, including controlled dimensions and volume fractions.[6–9] The drops can also be efficiently filled with active materials: typically, encapsulations of 100% efficiency can be achieved, whereas, by contrast, bulk methods achieve less than 10% of the actives encapsulated.[10,11] However, there are also disadvantages to using microfluidics to make double emulsions. A very important limitation is that microfluidic devices produce emulsions very slowly, because the small sizes of the channels, and their high hydrodynamic resistances, necessitate slow flow rates. For example, double emulsions are typically formed at a rate of only a few millilitres per hour, far too slow for most applications.[7,9] For microfluidic techniques to be useful for applications that require larger quantities, a method to produce the emulsions more quickly is needed.

One way to increase production is to parallelize the drop makers: rather than a single drop maker producing a small quantity of double emulsions, many can be used simultaneously, to produce much larger quantities.[12] However, parallelization of double emulsion synthesis in particular is very challenging, because of the complexity of the requisite devices, and the need to fabricate them with a high degree of uniformity. For example, a typical double emulsion device consists of two drop making junctions in series, with the wettabilities of the drop makers patterned such that one is hydrophobic and the other hydrophilic;[9,13] this is usually achieved by fabricating the channels first using a molding process, and then applying a post-fabrication treatment to spatially pattern wettability.[14–16] However, fabricating large numbers of the devices this way with a high degree of uniformity is very difficult, and this impedes parallelization. For microfluidic techniques to be useful for large scale synthesis applications, alternative methods for increasing the production are needed.

In this paper we present a method to increase, by several orders of magnitude, the production rate of double emulsions with microfluidic devices. Our strategy is based on the recognition that the maximum volumetric rate with which a device forms drops scales with the dimensions of the drop maker nozzle: larger nozzles yield larger volumes of multiple emulsions per unit time.[17,18] However, the increased dimensions also result in larger drops, which are undesirable for most applications. To produce drops of the desired small size, we split the large drops into small drops using a splitting array.[19] Each time a drop flows through a split, it is bisected into two equal portions; by splitting additional times, smaller though still monodisperse drops are formed.

Results and discussion

The maximum rate at which a device forms monodisperse drops is determined by the dripping-to-jetting transition; this occurs for a maximum value of the inner phase flow velocity v_{in}.[20] The production rate of the emulsion, however, does not scale with v_{in}, but with the volumetric flow rate $U_{in} = v_{in}A$, where A is the cross-sectional area of the drop maker. Therefore, even for fixed flow velocity, throughput can be increased by scaling up A. However, this also results in the production of larger drops, since, for drop formation in which plugging effects are important, $v_{drop} = WA(1 - \alpha U_{in}/U_{out})v_{drop}$, where v_{drop} is the drop volume, W the cross-sectional width of the drop maker nozzle, α a geometrical parameter close to one, and U_{out} the flow rate of the outer phase;[17] based on this $D_{sphere} \approx \sqrt[3]{wA}$. To obtain drops of the

School of Engineering and Applied Sciences/Department of Physics, Harvard University, Cambridge, Massachusetts, USA. E-mail: weitz@seas.harvard.edu; Tel: +1 617-495-3275

† Electronic supplementary information (ESI) available: Movies of single and double emulsion drop formation; movies of splitting of single and double emulsion drops. See DOI: 10.1039/c0lc00706d

desired small size, we split these large drops into small monodisperse drops using a splitting array.

A splitting array consists of a series of channels that divide into two channels several times.[19] When a drop encounters one of the forks, viscous and pressure forces pull it down each branch. Depending on flow conditions, channel dimensions, and the interfacial tension of the fluids, the drop can either choose one path, remaining intact, or follow both paths, splitting in two. If the drop splits the size of the resultant drops depends on the hydrodynamic resistances of the branches after the fork; for equal resistances, drops are split evenly, resulting in a monodisperse emulsion containing twice as many drops of half the original volume. Additional splits can be added to produce smaller drops; each level halves the volume, so that every three divisions halves the diameter. This allows selection of the final drop size by choosing the number of splits. Moreover, the rate of splitting is not limited by the final size of the drops, since with each split channels are added; this is in essence a form of parallelization, though the parallelization occurs after the drops have been formed.

To illustrate the use of splitting for increased production, we use it to create a monodisperse single emulsion at high throughput. We use water for the droplet phase and HFE-7500 fluorocarbon oil, with the ammonium salt of Krytox 157 FSL at 1.8 wt% as the surfactant, for the continuous phase. To enable production of water-in-oil drops, we make the device hydrophobic by treating with Aquapel. This is achieved by flushing Aquapel through the device for a few seconds, flushing with air, and then baking the device at 65 °C for 20 min.

The water and oil are injected into the device and meet in the cross-channel junction, where a water jet is formed, as shown in the upper portion of Fig. 1A and Movies available in the ESI†. Since the flow rates are close to the dripping-to-jetting transition, the jet is unstable, having ripples on its interface that are on the verge of breaking it into drops. Normally, the jet would break randomly, producing polydisperse drops; however, by adding a constriction downstream, we induce it to break into quite monodisperse drops,[21] as shown in Fig. 1A and Movies available in the ESI†. Due to the dimensions of the nozzle, 50 μm in height and 120 μm in width, the resultant drops are large, with diameters of 88 μm when spheres. To produce drops of the desired 35 μm size, we split the large drops $(88\ \mu m/35\ \mu m)^3 \approx 4$ times into $2^4 = 16$ equal portions. The maximum production rate of this device is 7000 μl h^{-1}; to produce drops of this size directly would require a nozzle of dimensions 25 μm in height and 25 μm in width, having a maximum rate of only ~600 μl h^{-1}. The ability of this technique to increase the production rate is limited by the fabrication. To increase the production rate further would require an even larger drop maker and a splitting array with even more channels. At some point, it becomes challenging to fabricate a drop maker of the needed size and the massive numbers of splitting channels needed to achieve the desired final drop size.

Splitting can also be used to increase the rate of double emulsification. We again add a splitting array to the end of a large drop maker, though this time it is a double emulsion maker. The double emulsion device consists of two cross-channel junctions connected in series, as shown in Fig. 1B and the upper row of images in Fig. 2. To make the double emulsions, we inject octanol, water with SDS at 1 wt%, and HFE-7500 with the

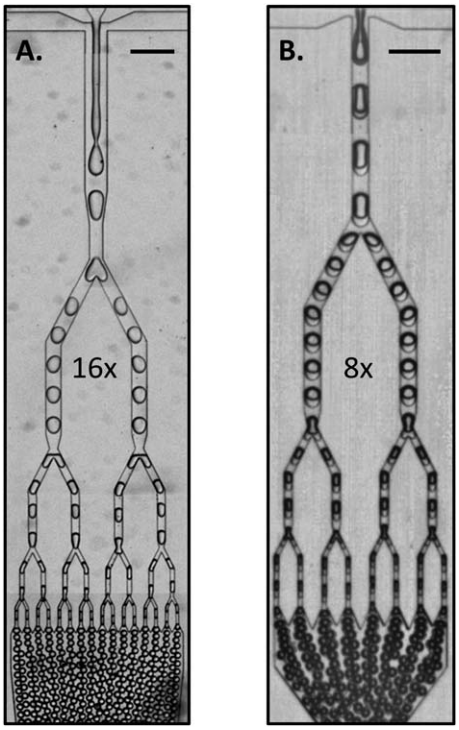

Fig. 1 Single and double emulsion splitting arrays for production of monodisperse emulsions at high throughput. The devices are fabricated in poly(dimethylsiloxane) using the techniques of soft lithography. The single emulsion device (A) splits the drops four times, into 16 equal portions, while the double emulsion device (B) splits only three times, into 8 equal portions. The single emulsion device operates at a throughput ~10× faster than a conventional drop maker, while the double emulsion operates ~5× faster; the slower speed of the double emulsion device is due to the fewer number of splits. The scale bars denote 200 μm.

Krytox surfactant at 1.8 wt% into the inner, middle, and continuous phase inlets, at 200, 500, and 1000 μl h^{-1}, respectively. This forms a stable jet of octanol in water in the first junction, which enters the second junction where the oil is added. This creates a coaxial jet of octanol surrounded by a sheath of water, which is itself surrounded by oil. As the coaxial jet enters the second junction, it becomes unstable, causing the outer interface to narrow, squeezing on the octanol jet. When the coaxial jet reaches an unstable width, it snaps, producing a double emulsion consisting of a water drop with an octanol core, as shown in Fig. 1B, the upper row of Fig. 2, and in Movies available in theESI†. This "one-step" pinching is distinct from the usual two-step process used to form double emulsions, because here the creation of the inner drops is driven by the pinching of the outer drops.[22] Because of the large dimensions of our device, the double emulsions are large, with diameters of 110 μm when spheres.

To split the double emulsions to create drops of the desired size, we again use a splitting array, as shown in Fig. 1B. When a double emulsion enters one of the splitting junctions, two lobes develop, one in each branch of the fork, as shown for $t = 0$ to 1.00 ms in the second row of Fig. 2 and in Movies available in the ESI†. As the double emulsion drop continues forward, the back interface approaches the apex of the fork; the lobes lengthen, eventually remaining connected by only a narrow coaxial thread;

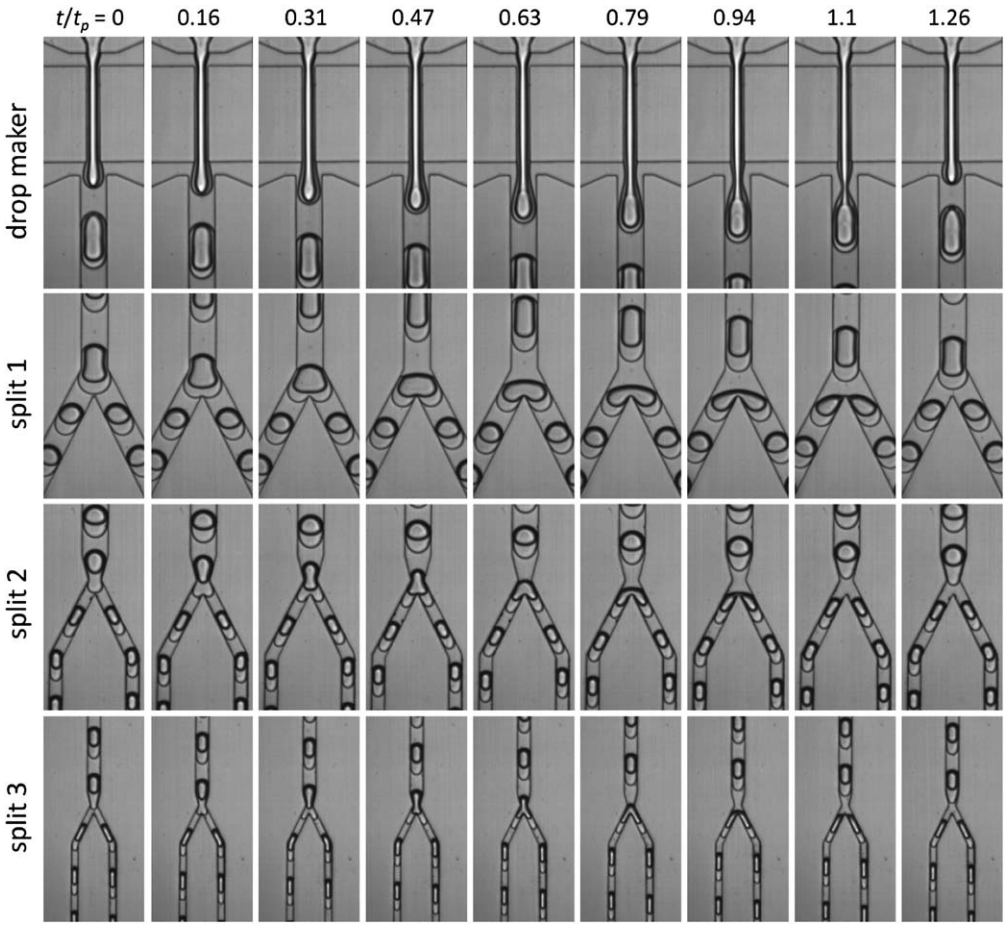

Fig. 2 Image sequences of double emulsions being formed using one-step double emulsification (top row) and being split into smaller drops using splitting junctions (lower rows). The device bisects the double emulsions three times, into daughter drops with a volume 1/8th that of the original parent drop. The splitting junctions narrow after each stage, to enable effective splitting of the smaller drops. The final drops are 43 μm in diameter when spheres.

the thread consists almost entirely of octanol, surrounded by a sheath of water, as shown for $t = 1.50$ ms in the second row of Fig. 2. As the thread narrows the outer interface squeezes on the octanol, narrowing it, and causing it to eventually snap, dividing the double emulsion drop into two, as shown in Fig. 2. These double emulsions are split into even smaller drops by the next two forks in similar processes, as shown in the time sequences in the lower rows of Fig. 2 and in Movies available in the ESI†. The same splitting process can also be applied to the formation of water-in-oil-in-water double emulsions, as shown in the Movie, ESI†. In this instance, the production rate is even faster, because the parent drop maker can be operated at higher flow rates before reaching jetting, due to the lower viscosity of the water inner phase compared to octanol.

To quantify the dynamics of splitting, we measure the lengths of the drops along their central axes as a function of time, Fig. 3. The single emulsion drops enter the splitting junction as a sausage shape, because they are initially confined in the narrow inlet channel. As they enter the fork, the two lobes develop; they initially do not entirely plug the channels, but allow the continuous phase to pass around them. During this time, the drop length decreases slowly, as shown in Fig. 3A, left. When the lobes grow to a sufficient size, they plug the channels; this restricts the

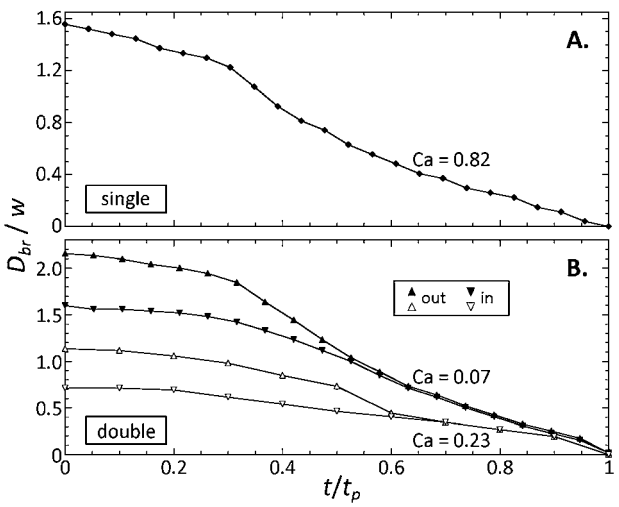

Fig. 3 Lengths of (A) single and (B) double emulsion drops as a function of time, measured from their back interfaces to the apex of the fork in the splitting junction; the lengths are normalized by the width of the channel leading into the junction. For the double emulsions, the lengths of both the outer drops (L_{out}) and inner drops (L_{in}) are provided. The experiment is also performed at different capillary numbers, as labeled.

path of the continuous phase which must now move through gutters at the corners of the channels and thin lubricating layers between the lobes and walls. This increases the resistance of the channels to the continuous phase, causing the pressure to increase behind the drop. This propels the drop faster into the splitting junction, so that its length decreases more sharply, as shown in Fig. 3A, middle-left. From this point forward, the decrease is approximately linear as a function of time, up until the moment of pinch off, as shown in Fig. 3A, right.

The splitting of double emulsions follows a similar process, though it consists of two decays corresponding to the splitting of the outer and inner drops. For the outer drops, we again observe a two-step decay: a slow initial decay as the lobes develop, followed by a faster decay afterwards, as shown in Fig. 3B. Interestingly, for the inner drops there is also a two-step decay, although by the second step the length of the inner drop is nearly equal to that of the outer drop. This means that the thread connecting the lobes is almost entirely inner fluid, sheathed by a thin layer of middle fluid, as shown at $t = 1.50$ ms for rows 2–4 in Fig. 2. This is reminiscent of the one-step breakup of the coaxial jet when forming the double emulsions. As in that process, the outer interface appears to drive the narrowing of the inner drop, as demonstrated by the simultaneous narrowing of both threads in Fig. 3B. When the thread achieves a critical width, it becomes unstable, snapping and dividing the double emulsion into two, as shown in Fig. 3B.

Our data also show that there are two kinds of splitting processes: a continuous narrowing of the thread and a discontinuous narrowing, and these depend on the capillary number (Ca) of the flow. This can be explained by considering the timescales associated with splitting. Splitting consists of two processes, the initial distortion of the drop as it is pushed into the junction and the final pinch off of the thread connecting the lobes. Whereas the initial distortion is governed by channel geometry, interfacial forces, and the pressure drops through the fork, and is thus dependent on the flow-velocity, the final breakup occurs due to the Rayleigh–Plateau instability, and is independent of the flow velocity. Therefore, at low Ca, the shape distortion is slow compared to pinch off, because the flow velocity is slow; this produces the discontinuous thread evolution, in which pinch off is sudden compared to other dynamics. By contrast, at high Ca when the flow velocity is fast, the rate of distortion is comparable to that of the pinch off, resulting in continuous evolution of the thread.

When implementing these techniques, there are important factors that must be considered to ensure equal, robust splitting. The ability of a junction to split a drop depends on the diameter of the junction with respect to that of the drop; if the drop is large, the lobes can plug the downstream channels, resulting on good splitting. We find that the narrow constriction ahead of the junction aids this, because it allows the lobes to more effectively plug the downstream channels, for more robust splitting. The channel lengths after the split are also important; they should be several times longer than the drops, because if they are too short, contributions to the resistance of these channels due to the drops can become significant, resulting in feedback between parallel channels that can cause irregular drop flow, interfering with splitting. For example, this can cause all the drops to move through one path, leaving the other channels empty; the path can switch spontaneously in response to small perturbations, in analogy with an electronic flip-flop.[23,24] By increasing the lengths of these channels, we increase their resistance, minimizing contributions due to the drops, and preventing such feedback effects. This ensures more robust, uniform splitting.

The Ca of the flow is also important. For optimal splitting, the Ca should be neither too low nor too high. If too low, drops may not split, or the inner drops may burst through the middle phase, coalescing with the continuous phase. By operating at high Ca, these effects are suppressed in two ways. Between the inner and continuous phases is a thin lubricating film of middle phase that secures the inner drop within the middle drop; from lubrication analysis, the film thickness scales with the $Ca^{2/3}$;[25] increasing the Ca thus makes the film thicker, enhancing the stability. Moreover, increasing the Ca also minimizes the time the drops spend in the splitting junction, limiting drainage of the film, and further minimizing rupture. However, too high a Ca is also problematic, because it leads to production of satellite drops. Satellites form during the final pinching of the thread. As the thread narrows and the interface squeezes inward, the fluid is driven out of the thread and into the lobes. However, if the Ca is large, viscous effects dominate over interfacial ones; the viscosity of the liquid resists the pinching, causing some fluid to get trapped in the thread, becoming satellites.

For optimal splitting, the Ca should thus be neither too high nor too low. The optimal value is just above what is needed for splitting, which occurs for a fixed flow velocity.[19,26] However, while it is simple to select the best Ca value for a single split, it is more difficult to do this for multiple splits, because as splits are added the fluid is divided into an increasing number of channels, thus reducing the flow velocity. One solution is to simply increase the total flow rate to ensure Ca is sufficiently high for all junctions; however, this will cause the Ca to be very high in the first junctions, leading to satellites. Our solution is to adjust the channel dimensions so that as splits are added the Ca is maintained constant. This is achieved by gradually narrowing the channels as splits are added, to maintain the total cross-sectional area of the channels constant.

Splitting arrays are thus effective for producing drops at high rates. However, for this to be useful for most applications, the drops must also be monodisperse. To confirm that this method produces monodisperse drops, we measure the size distributions of samples from the devices. For the single emulsion device, we split the drops into 16 portions, producing drops with a final average diameter of 35 μm and a narrow distribution, with a coefficient of variation (CV) of 5%, as shown in Fig. 4A and C. For the double emulsions, we split the drops into eight equal portions, producing final drops with average inner and outer diameters of 28 μm and of 43 μm, each with a narrow size distribution, CVs of 6%, as shown in Fig. 4B and D.

Splitting can thus be used to produce very uniform single and double emulsions; however, these emulsions are not quite as monodisperse as those formed using a single drop maker, which typically achieve CVs of less than 1%. We believe this to be a consequence of imperfect device fabrication, rather than limited control in the splitting process. From observations of uneven splitting, we find that asymmetric splits always occur in the same splitting junctions, suggesting that fixed geometrical properties are to be blamed. Uneven splitting is known to occur

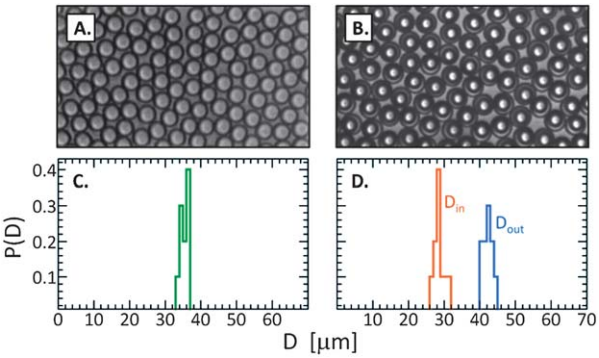

Fig. 4 Images of (A) single and (B) double emulsions, and the corresponding diameter distributions in (C) and (D), respectively. The coefficients of variation for the distributions are 5–6%, quite small, but still higher than is typically achieved with a single drop maker, a consequence of imperfect fabrication of the splitting channels.

when the branches of the split have unequal hydrodynamic resistance: the arm with the lower resistance always forms the larger drops. With our fabrication, we are able to achieve uniformity in the channel dimensions of ~1 μm. Under laminar flow conditions, a channel of rectangular cross-section has a hydrodynamic resistance,

$$R_{\mathrm{hyd}} = 12\left[1 - \frac{192h}{\pi^5 w}\sum_{n=1,3}^{\infty}\frac{1}{n^5}\tanh\left(\frac{n\pi w}{2h}\right)\right]\frac{\mu L}{wh^3}$$

where h and W are the height and width of the channel, respectively, and μ is the viscosity of the fluid flowing through it.[27] The limited resolution of the fabrication is thus expected to produce a variation in channel resistance of ~15%. From empirical observations, the volume of the drops after splitting $V_l/V_r \approx R_r/R_l$, where V_l and V_r are the volumes of the drops and R_r and R_l the hydrodynamic resistances for the left and right branches, respectively;[19] from this, we estimate a variation in the drop diameter to be ~8%, which is close to the observed polydispersity. This indicates that the increased polydispersity we observe, while quite small, is a consequence of the limited precision of the device fabrication. A simple way to reduce the polydispersity is to increase fabrication precision, possible using higher resolution photomasks. Another approach would be to lengthen the channels after the split; this should allow variations in cross-sectional dimensions to average out down the length of the channels, for more uniform resistances, and lower polydispersity.

Conclusions

Serial droplet splitting is a simple way to increase the production rates of microfluidic single and double emulsion makers. The throughput is ultimately limited by the size of the drop maker feeding the array, since this sets the maximum flow rate that can produce monodisperse drops. We have constrained ourselves to devices with constant channel height, limiting the maximum size of the drop makers leading into the splitting array. While this allows us to achieve throughput increases of approximately an order of magnitude, much larger increases should be possible using multi-height channels, which would allow larger drop makers to be coupled to splitting arrays with even more channels. For example, using two channel heights, a 300 μm drop maker could be used to feed a splitting array of 1000 channels; this would break each 300 μm drop into one thousand 30 μm drops, increasing the production throughput by three orders of magnitude. The simplicity and speed of this technique should make it attractive for applications requiring rapid, monodisperse emulsification, for example, for scaled-up particle and capsule synthesis.

Acknowledgements

We thank Connie Wilking, Assaf Rotem, Christian Holtze, and Mark Romanowski for helpful discussions. This work was supported by the NSF (DMR-0602684), the Harvard MRSEC (DMR-0820484), and the Massachusetts Life Sciences Center.

References

1 W. Seifriz, *J. Phys. Chem.*, 1925, **29**, 834–841.
2 N. Garti, *Colloids Surf., A*, 1997, **123**, 233–246.
3 A. Edris and B. Bergnstahl, *Nahrung*, 2001, **45**, 133–137.
4 Y. Y. Yang, T. S. Chung and N. P. Ng, *Biomaterials*, 2001, **22**, 231–241.
5 I. G. Loscertales, A. Barrero, I. Guerrero, R. Cortijo, M. Marquez and A. M. Ganan-Calvo, *Science*, 2002, **295**, 1695–1698.
6 S. Okushima, T. Nisisako, T. Torii and T. Higuchi, *Langmuir*, 2004, **20**, 9905–9908.
7 A. S. Utada, E. Lorenceau, D. R. Link, P. D. Kaplan, H. A. Stone and D. A. Weitz, *Science*, 2005, **308**, 537–541.
8 L. Y. Chu, A. S. Utada, R. K. Shah, J. W. Kim and D. A. Weitz, *Angew. Chem., Int. Ed.*, 2007, **46**, 8970–8974.
9 A. R. Abate and D. A. Weitz, *Small*, 2009, **5**, 2030–2032.
10 H. C. Shum, J. W. Kim and D. A. Weitz, *J. Am. Chem. Soc.*, 2008, **130**, 9543–9549.
11 D. Lee and D. A. Weitz, *Small*, 2009, **5**, 1932–1935.
12 T. Nisisako, T. Torii, T. Takahashi and Y. Takizawa, *Adv. Mater.*, 2006, **18**, 1152.
13 M. Seo, C. Paquet, Z. H. Nie, S. Q. Xu and E. Kumacheva, *Soft Matter*, 2007, **3**, 986–992.
14 A. R. Abate, A. T. Krummel, D. Lee, M. Marquez, C. Holtze and D. A. Weitz, *Lab Chip*, 2008, **8**, 2157–2160.
15 A. R. Abate, J. Thiele, M. Weinhart and D. A. Weitz, *Lab Chip*, 2010, **10**, 1774–1776.
16 M. B. Romanowsky, M. Heymann, A. R. Abate, A. T. Krummel, S. Fraden and D. A. Weitz, *Lab Chip*, 2010, **10**, 1521–1524.
17 P. Garstecki, M. J. Fuerstman, H. A. Stone and G. M. Whitesides, *Lab Chip*, 2006, **6**, 693–693.
18 P. Garstecki, M. J. Fuerstman, H. A. Stone and G. M. Whitesides, *Lab Chip*, 2006, **6**, 437–446.
19 D. R. Link, S. L. Anna, D. A. Weitz and H. A. Stone, *Phys. Rev. Lett.*, 2004, **92**, 054503.
20 T. Cubaud and T. G. Mason, *Phys. Fluids*, 2008, **20**, 053302–053311.
21 W. A. C. Bauer, M. Fischlechner, C. Abell and W. T. S. Huck, *Lab Chip*, 2010, **10**, 1814–1819.
22 A. R. Abate, J. Thiele and D. A. Weitz, *Lab Chip*, 2011, **11**, 253–258.
23 M. J. Fuerstman, P. Garstecki and G. M. Whitesides, *Science*, 2007, **315**, 828–832.
24 M. Prakash and N. Gershenfeld, *Science*, 2007, **315**, 832–835.
25 F. P. Bretherton, *J. Fluid Mech.*, 1961, **10**, 166–188.
26 A. M. Leshansky and L. M. Pismen, *Phys. Fluids*, 2009, **21**, 023303.
27 R. K. Shah and A. L. London, *Laminar flow forced convection in ducts: a source book for compact heat exchanger analytical data*, Academic Press, New York, 1978.