Holographic control of droplet microfluidics

Maria-Luisa Cordero, Daniel R. Burnham, Charles N. Baroud and David McGloin

LadHyX and Department of Mechanics, Ecole Polytechnique, 91128 Palaiseau cedex, France
SUPA, School of Physics and Astronomy, University of St Andrews, North Haugh, St Andrews, KY16 9SS, UK
Electronic Engineering and Physics Division, University of Dundee, Nethergate, Dundee, DD1 4HN, UK

ABSTRACT

Droplet microfluidics is an emerging area in miniaturisation of chemical and biological assays, or "lab-on-a-chip" devices. Normally consisting of droplets flowing in rigid microfluidic channels they offer many advantages over conventional microfluidic design but lack any form of active control over the droplets. We present work, using holographic beam shaping, that allows the real time reconfigurability of microfluidic channels allowing us to redirect, slow, stop, and merge droplets with diameters of approximately 200 microns. A single beam is be sufficient to perform simple tasks on the droplets but by using holographic beam shaping we can produce multiple foci or continuous patterns of light that enable a far more versatile tool.

Keywords: optical tweezers, digital microfluidics

1. INTRODUCTION

Microfluidics and optical manipulation are two independently maturing technologies that enable advanced studies of objects at the micron-scale. Since the invention of optical tweezers [1] optical manipulation has developed through many differing technologies with one of the major advances being dynamic holographic optical trapping (HOT) [2, 3]. HOTs are currently a versatile tool in standard colloidal studies [4] and are providing increasingly complex possibilities in the control of droplets in the micrometer range [5, 6]. Currently manipulation through optical forces alone is limited to micron size regimes but here we extend the idea that optics can induce a process which itself creates far larger forces and hence can act on a larger size regime [7].

Developing in parallel, but independently, microfluidics technology aims to provide automation through the miniaturization of fluid handling systems to enable efficient and highly parallel measurements of, in particular, biological and chemical processes. Many approaches are being explored towards this goal, of which the manipulation of droplets in microchannels is one of the most promising routes [8-10]. In this binary like “digital microfluidics”, each droplet can be thought of as an independent vessel containing a reaction one may want to perform repeatedly, for example in the case of controlled chemical synthesis [9], or, instead, vary the parameters of in order to explore a large number of combinations [10-12].

Two main technologies have surfaced recently that allow the manipulation of these droplets. The first is based upon application of an electric field to produce a force on the drop due to the dielectric contrast between the two liquids. This approach has been shown to work in sorting [13] and merging droplets [14, 15]. The second technique varies the surface tension of the droplets locally, through the use of a focused laser beam, thus inducing a thermocapillary force on the drop. This action can produce a net force that can block the formation of drops, carry out simple routing [16], fuse them, synchronize them, or control their division [5].

Here we demonstrate that the combination of microfluidics with reconfigurable optical holographic methods extends the possibilities of droplet manipulation. The contactless nature of optical manipulation allows the use of different laser patterns to implement complex operations that are not possible using the current electrical forcing methods. We investigate the effect of the laser beam’s shape on the blockage of droplets. The ability to vary the shape of the laser beyond a simple Gaussian beam provides an additional degree of freedom which can extend the limits of the technique. We go on to demonstrate novel implementations which show conceptually new operations on drops in microchannels.
2. EXPERIMENTAL

The techniques of holographic optical tweezers were employed [17] to manipulate droplets in microchannels. There is one key difference between our approach and standard optical tweezers – here the forces are only indirectly produced by the application of the laser beam. So we have no need for the use of high NA optics, as optical gradient forces will not affect droplets of the sizes used (~ 200 µm). A diagram of the apparatus is shown in figure 1. The Gaussian beam from a 4W Laser Quantum Finesse laser providing continuous wave 532 nm light was expanded using a Keplerian telescope to entirely fill the short axis (768 pixels) of a Holoeye LCR-2500 spatial light modulator (SLM). Power was controlled with a polarizing beam cube and half wave plate, whilst a second half wave plate rotated the polarization to achieve optimal diffraction efficiency from the SLM. Two 4f imaging systems demagnified the phase modulated beam so the SLM was conjugate with the microscope objective’s back aperture whilst slightly under-filling the pupil. Two objectives were used over the course of the experiments; the first was a Nikon 10x (NA=0.25) and the second a Mitutoyo 10x (NA=0.26) both of which focus the beam into the prefabricated microfluidic channels positioned on a 3 axis translation stage above the objective. The two objectives, in conjunction with custom built Kohler illumination and appropriate tube lenses, were also used to image the channels onto a Basler A602f firewire camera.

![Diagram of the experimental apparatus](image)

The phase of the beam incident upon the SLM was modified by displaying phase-only holograms (kinoforms) whose optical Fourier transform gives the desired intensity pattern in the plane of the microfluidic channel. To produce the holograms we implemented an adaptive-additive algorithm [18] in custom written LabVIEW software, allowing the user to input an arbitrary 8-bit greyscale image of the desired intensity pattern. It must also be noted that the Holoeye SLM is not optically flat and induces a relatively large amount of aberration. This non-flatness is measured using a simple method [19] allowing the calculation of a correction hologram which is combined with the phase changing hologram to remove the large amount of astigmatism inherent in the device.
The microfluidic chips were fabricated with molded PDMS (Sylgard 184, Dow Corning) using standard soft lithography techniques and sealed against a glass microscope slide. The dimensions of the channels ranged from 75 to 200 µm in width and were 50 µm in height. Oil (Hexadecane + span80, 2% w/w) and an aqueous solution (water + ink 2% v/v) are injected into the channel using syringe pumps. Dark blue Parker pen ink was added to the water in order to absorb the 532 nm light. Were chemically, biologically, or physically sensitive material to be placed within the droplets it is possible to use other absorbing dyes depending on absorption requirements and the laser wavelength used [7].

In order to investigate the effect of different light patterns on drops, we investigated the minimum optical power, $P_{\text{min}}$, required to block the advance of a drop, for three different shapes: a Gaussian spot with a 1 µm beam waist, a straight line aligned along the flow direction, and a straight line orthogonal to the flow direction. Both lines were 2 µm in width and 200 µm microns in length. The PDMS microchannels had two oil inlets and one for aqueous solution. Droplet size is determined by the ratio between the first oil flow rate $Q_{\text{oil-1}}$ and the water flow rate $Q_{\text{water}}$, which were both kept constant. The second oil flow rate $Q_{\text{oil-2}}$ was used to tune the total flow rate $Q_{\text{tot}} = Q_{\text{oil-1}} + Q_{\text{oil-2}} + Q_{\text{water}}$. This enabled the size of the droplets to be kept constant while their velocity varied with $Q_{\text{tot}}$.

A close up photograph of the microfluidic area is shown in figure 2. The tubes on the left act as drains for the discarded fluid while those on the right input the oil and water into the appropriate channels. Also note the large working distance created by the objective and condenser which makes this a very accessible apparatus.

![Fig. 2. Close up view of the actual experiment. The pipes to the right inject the oil and water to the appropriate channels. The three pipes to the left are drains for the channels. The long working distance of condenser and microscope objective provide ample space for the ‘chip’ and combined with the relatively simple optical system in figure 1 provides a simple to use versatile system. As an aside the bottle into which the drains are fed gives an indication of just how little fluid is used in such a system even over the space of a week.](image1)

### 3. RESULTS

The first observation, as the drops reach the laser beam, is that the water-oil interface adapts to the laser shape, as seen in figure 3. When the line is parallel to the direction of flow, the front interface is flattened and the drop stops after advancing through a significant portion of the line. In the case of a line perpendicular to the flow direction, the surface of the drop is even flatter than in the previous case, taking on the shape of the line. For a Gaussian beam the drop behaves similarly to the former case but not with such magnitude.
Fig. 3. The effect of (a) a line parallel to the flow, (b) a line perpendicular to the flow, and (c) a Gaussian beam, upon the profile of a droplet. It is clear in image (b) the droplet morphs to match the pattern.

For each optical pattern used the total flow rate was varied from $Q_{\text{tot}} \sim 1$ to $11 \text{nL/s}$ in increments of $0.17 \text{nL/s}$ and for each rate we started at high laser power reducing it for successive drops, until the minimum power $P_{\text{min}}$ that still held the drops was reached. The maximum flow rate attained was limited by the water in the drops boiling, not by the laser no longer blocking the droplets.

The minimum laser power for each of the laser distributions is plotted against the total flow rate in figure 4. Each scales approximately linearly with flow rate and gradients and values of $P_{\text{min}}$ differ for the three cases. The use of a line perpendicular to the flow allows the blocking of drops at higher flow rates, up to more than $10 \text{nL/s}$. Conversely, even though a lower laser power is necessary to hold the droplets in the case of a Gaussian spot, it was not possible to hold droplets for flow rates higher than about $5 \text{nL/s}$. This was also the case for the line parallel to the flow.

Fig. 4. Minimum laser power required to block a drop at varying flow rates for a Gaussian beam and lines parallel and perpendicular to the direction of flow.

If the pattern intensity is calculated and plotted instead, the minimum intensity $I_{\text{min}}$ necessary to block a droplet is found to be several times higher for a Gaussian spot than for a line distribution as shown in figure 5. The perpendicular line is found to block droplets for the lowest value of $I_{\text{min}}$. 

---

Proc. of SPIE Vol. 7038  70381J-4
We will now consider the advanced operations made possible by the use of holographic beam shaping and how single spot applications [7] can be extended.

3.1 Routing (Simple sorting)

First we show three-way droplet routing, actively sending droplets into different directions at a trifurcation. Making use of the ability to both dynamically switch the optical patterns projected into the microfluidic channel and the ability to create extended patterns (in this case four spots) we can deflect droplets through large angles and send them into preferred channels. This is shown using a four way cross channel in figures 6(a), (b) and (c) which shows the droplets being moved to the left, straight, or to the right, respectively. The switching time of the droplets into a given channel is limited only by the update speed of the SLM, which ranges from 30 to 60 Hz. With integration of simple image recognition software and hologram switching this could provide a robust method for sorting in digital microfluidics, one of the major applications of microfluidics. One could imagine the sorting being based on droplet size, chemical composition, fluorescence measurements or simply the contents of a drop.
Fig. 6. Four Gaussian beams are aligned to sort droplets into either (a) the left-hand channel, (b) the center channel, or (c) the right channel. The insets show the positions of the holographically generated multiple Gaussian foci within the channel.

3.2 Storage and reordering

Next we show an example that goes beyond simple Gaussian spots to use line patterns to store droplets at given points in the channel while rerouting other droplets to move past the stored droplet. The line patterns produced cannot be treated like a simple Gaussian beam and exist with relatively lower fidelity over the same axial distance but remain sufficiently intact to produce the desired effect. Snapshots from an example video using such lines are shown in figure 7. The first line upstream is set to move a droplet into one side of the larger channel. The droplet is then stored by the downstream line further along the channel. The first line is then changed so as to move subsequent droplets in the flow past the first droplet. Thus we can store and could interrogate the first droplet without the need to stop the flow, which is important in order to obtain longer interrogation times. Note that the ability to focus the laser to a small area on the drop allows real droplet-level manipulation, contrary to electrical fields which produce a uniform forcing on a region of the microchannel [13]. This is what allows the drop order to be inverted in this case.

Fig. 7. Image sequence (left column followed by right column) showing how the droplet re-ordering. The initial drop is sent down and held stationary and droplets thereafter are sent up past the first. Dashed lines overlay the position of the laser patterns.
3.3 Multiple Storage (Memory)
Extending the previous idea we can begin to store multiple droplets, shown in figure 8. Here we trap several droplets at once, first one, then two and finally three using three lines of light. Again this is in the presence of droplets flowing through the channel. We are then able to shuttle the droplets through the pattern, by turning the whole pattern on and off, so the first droplet is lost and the second droplet takes its place and so on. This allows large scale storage and controlled movement of many droplets simultaneously which may be useful for offline analysis of many droplets, droplet re-ordering or droplet “memory” applications.

Fig. 8. A drop treadmill holds up to three droplets and can function as a first-in-first-out buffer memory. The triangle marks the same droplet in the different images (sequenced left column followed by right column), indicating its movement. Dashed lines overlay the position of the laser patterns. Total power in the sample plane is ~475 mW.

Finally we show, in figure 9, the forces produced are large enough to stop droplets filling the whole channel or touching the channel walls. It is hoped with further work it may be possible to design microfluidic channels and optical fields that would allow “wall-less” microfluidics.

Fig. 9. Five spots are placed in a line parallel to one wall. Three are very visible, with two more to their left. In the left-hand image the laser is off and the droplet touches the top wall as it is formed. In the right-hand image the laser is on and the droplet is prevented from touching the upper wall.
4. DISCUSSION AND CONCLUSION

We have extended previous work that allows optical fields to induce the production of forces well above those possible from the electromagnetic field alone. Using techniques borrowed from the field of optical tweezers we have developed a system of microfluidic control whose purpose can be altered in real time.

Outlined above are just a few simple examples providing some novel operations. The system is sufficiently simple and user friendly that if the desired operation for a particular application does not exist it can be created with relative ease.

In conclusion this work demonstrates that holographic beam shaping has a number of advantages over conventional methods of inducing thermocapillary forces on droplets. Extended patterns of light offer significant additional functionality over techniques using a single optical tweezer, which can lead to enhanced control in droplet microfluidic devices.

ACKNOWLEDGEMENTS

The authors thank Emilie Verneuil for useful discussion, and also the British Council PHC Alliance Program for funding. M.-L.C. was funded by the EADS foundation and by MIDEPLAN. DM is a Royal Society University Research Fellow.

REFERENCES


