Fusion and sorting of two parallel trains of droplets using a railroad-like channel network and guiding tracks

Linfeng Xu, Hun Lee, Rajagopal Panchapakesan and Kwang W. Oh
SMALL (Sensors and MicroActuators Learning Lab), Department of Electrical Engineering,
University at Buffalo, The State University of New York (SUNY at Buffalo), Buffalo, New York 14260, USA

ABSTRACT

We propose a robust droplet fusion and sorting method for two parallel trains of droplets that is relatively insensitive to frequency and phase mismatch. Conventional methods of droplet fusion require an extremely precise control of aqueous/oil flows for perfect frequency matching between two trains of droplets. In this work, by combining our previous two methods (*i.e.*, droplet synchronization using railroad-like channels and manipulation of shape-dependent droplets using guiding tracks), we realized an error-free droplet fusion/sorting device for the two parallel trains of droplets. If droplet pairs are synchronized through a railroad-like channel, they are electrically fused and the fused droplets transit to a middle guiding track to flow in a middle channel; otherwise non-synchronized non-fused droplets will be discarded into the side waste channels by flowing through their own guiding tracks. The simple droplet synchronization, fusion, and sorting technology will have widespread application in droplet-based chemical or biological experiments, where two trains of the chemically or biologically treated or pre-formed droplets yield a train of 100% one-to-one fused droplets at the desired outlet channel by sorting all the non-synchronized non-fused droplets into waste outlets.

KEYWORDS: Droplet, Continuous Flow, Fusion, Sorting

INTRODUCTION

we introduce a robust droplet-based microfluidic device that can realize self-synchronization, electro-fusion, and sorting of two trains of frequency-mismatched and/or out-of-phase droplets. This is accomplished by combining our previous two methods: parallel self-synchronization of two trains of droplets using railroad-like channels[1] and manipulation of shape-dependent droplets using guiding tracks[2]. Moreover, we can perform error-free sorting depending on the droplet synchronization and fusion status. If droplets are synchronized through a railroad-like channel network, the paired droplets can be electrically fused at a fusion junction[3]. Then the fused droplets will follow a fusion guiding track into a middle outlet. Otherwise, droplets which are non-synchronized and/or non-fused largely due to pressure instability or congestion of the droplets, will be guided by waste tracks and discarded into side waste-outlets. In this study, we have investigated fusion efficiency and error rate with respect to droplet size, velocity, and frequency mismatch ratio.

PRINCIPLE

As shown by Fig. 1, because the channel thickness (T_{Channel}) is fabricated to be much thinner than the droplet diameter (D), droplets are squeezed into a pancake shape. By adding the guiding track structures, the pancake shape droplets will expand into a lid-with-handle shape with a smaller surface area. According to the surface energy (E) equation, $E = \gamma S$, with respect to the interfacial tension (γ) and the surface area of the droplet (S), the lid-with-handle shape droplet has lower surface energy than the pancake shape droplet. Hence, the flattened droplet will be confined to moving along the guiding track[4].

The gap between tracks (L_{Gap}) is set to be equal to the radius of the generated droplets ($D/2$), and the fusion distance (L_{Fusion}) is set to be slightly larger than the diameter of the fused droplets. Once two synchronized droplets exiting from the parallel channels touch each other at the fusion junction, they will be fused by electric force. Then, the fused droplet will be forced to move along the fusion track, as the geometric centre of the fused droplet will be positioned at the fusion track (*Fig. 1b*).

978-0-9798064-5-2/µTAS 2012/$20©12CBMS-0001

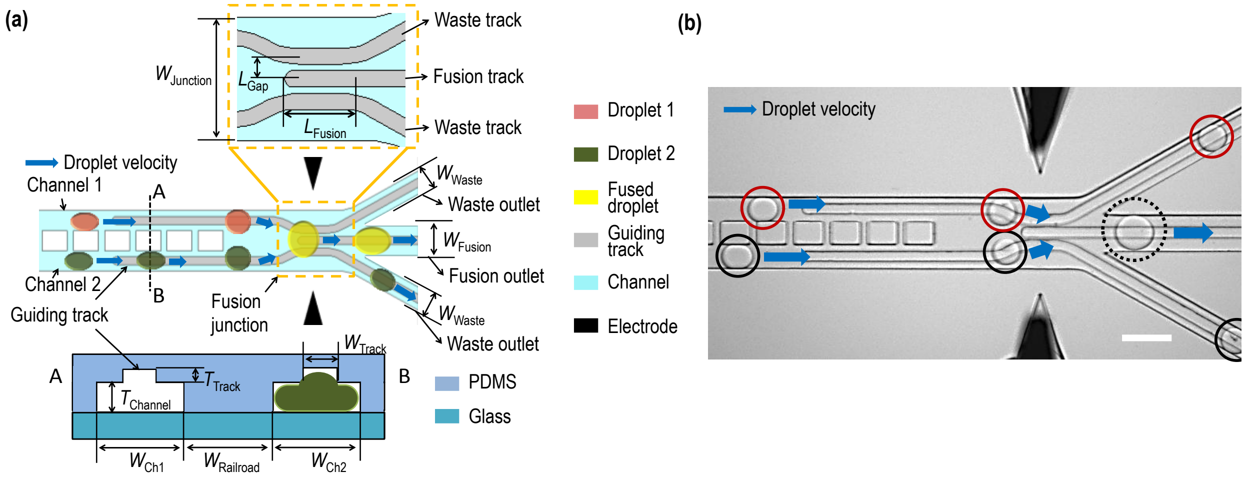


Figure 1 : Schematic view of the proposed device. (a) Top view and cross-section view. If paired-droplets synchronized through the railroad-like ladder structures meet at the junction, they will be electrically fused and the fused droplet will move to the fusion outlet. Otherwise, non-synchronized/non-fused droplets will follow the waste guiding tracks into the side waste outlets. Inset shows the enlarged view of the fusion junction. (b) Captured image of the real device in operation. Red circles point out the droplets from the channel 1, while black circles indicate the droplets from the channel 2. A fused droplet is shown in a dashed black circle. Scale bar is 200 µm.

EXPERIMENT/RESULTS

As the device has two separate droplet generation structures, two trains of droplets can be independently gen-

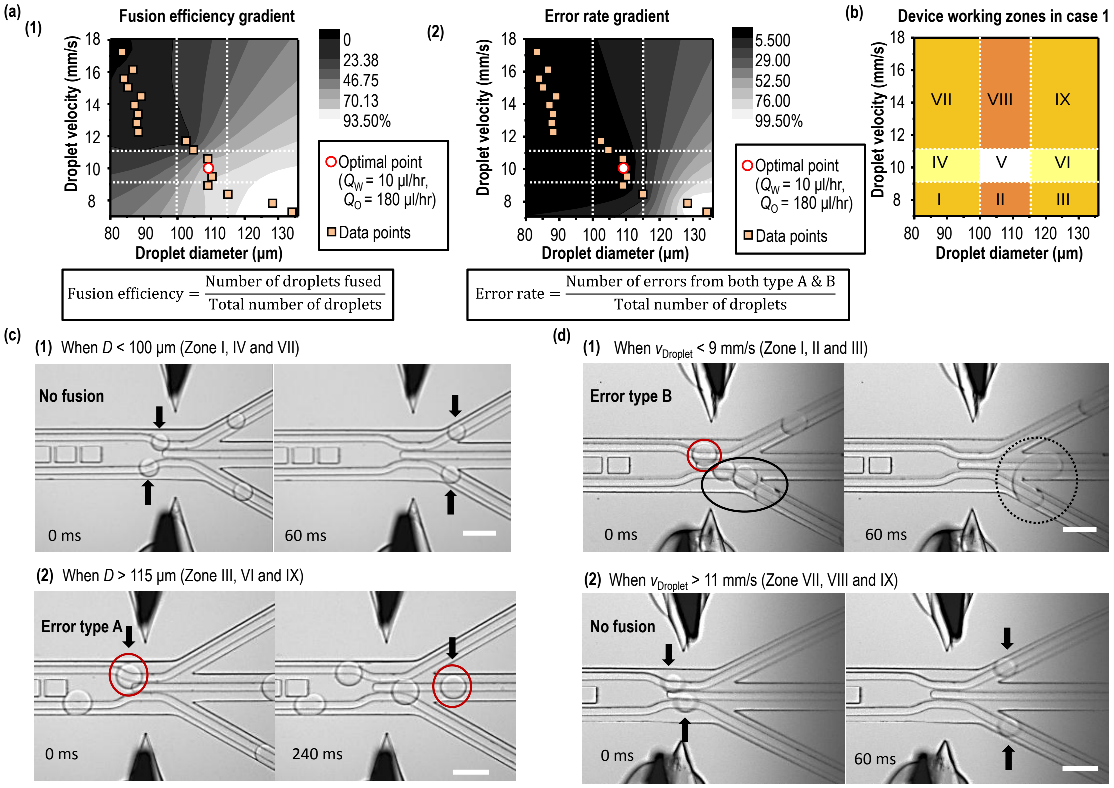
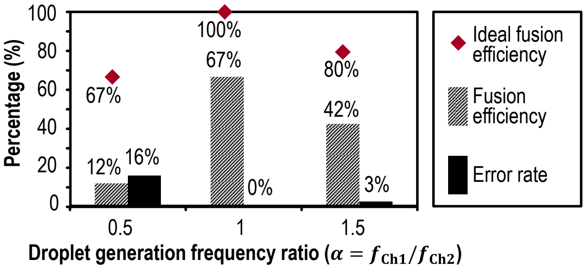


Figure 2 : Results and analysis of the proposed device. (a-1) Gradient graph of the fusion efficiency with respect to the droplet size and velocity. (a-2) Gradient graph of the error rate with respect to the droplet size and velocity. All the gradient graphs were plotted by experimental extrapolation using Origin 7.5. (b) Summary chart of the device's working zone. Zone V is the operation zone. (c-1) In Zones I, IV, and VII, droplets are successfully sorted without fusion due to their small size, causing low fusion efficiency. (c-2) In Zones III, VI, and IX, large, out-of-phase droplets are not fused and enter the wrong outlet, causing sorting failure (error type A). (d-1) In Zones I, II, and III, multiple-droplet fusion (more than two droplets) causes sorting failure (error type B). (d-2) In Zones VII, VIII, and IX, fast moving droplets are not fused without sorting failure. All scale bars are 200 µm.



$$\boxed{\text{Ideal fusion efficiency} = \frac{\text{\# of droplets from lower frequency channel} \times 2}{\text{Total \# of droplets}}}$$

Figure 3 : Analysis of the frequency-mismatched droplets in the proposed device. Fusion efficiency and error rate are plotted with different droplet generation frequency. Ideal fusion efficiency is defined as the ratio between the twice of the total number of droplets in the lower frequency channel and the total number of droplets from both the channel 1 and 2. For simplicity, the frequency is plotted by using the frequency ratio.

erated for each parallel channel. By controlling the flow rate ratio of water (Q_W) and oil (Q_O), we could achieve two different cases in terms of the frequency difference ($\Delta f = |f_{Ch1} - f_{Ch2}|$), where f_{Ch1} and f_{Ch2} are the droplet generation frequency in each parallel channel: (1) Case 1: the same (or similar) generation frequency ($\Delta f \approx 0$) and (2) Case 2: different generation frequencies ($\Delta f \neq 0$) for the two trains of droplets. In both cases, the droplet size was controlled to be the same (or similar) for the droplets generated in each channel ($\Delta D \approx 0$).

In Case 1 ($\Delta f \approx 0$) Fig. 2 summarizes the working conditions of our proposed device. For Zones I, II, and III, droplets are moving too slowly causing high fusion/sorting error rate, while for Zones VII, VIII, and IX, droplets move too fast resulting in low fusion efficiency. Similarly, in Zones I, IV, and VII, droplets are too small to be fused, while in Zones III, VI, and IX, large droplets cause a high rate of fusion/sorting errors. Based on our experiment, Zone V indicates a proper working range for the proposed device.

In Case 2 ($\Delta f \neq 0$), as shown by Fig. 3 when the frequency ratio was $\alpha = 1.5 > 1$, the fusion efficiency was reduced to 42% and the error rate was below 3%. On the other hand, for the case where the frequency ratio was $\alpha = 0.5 < 1$, the fusion efficiency was rapidly reduced to 12% and the error rate was increased to 16%. For $\alpha > 1$, the net droplet velocity will increase. This will allow less chance of droplet fusion due to the short contact time. However, for $\alpha < 1$, the fusion efficiency will drop and the error rate will increase abruptly. Due to the increased difference in the droplet generation frequency combined with the low droplet velocity, heavy droplet congestion will occur in the parallel channels, causing frequent fusion and sorting errors (error type B).

CONCLUSION

We have demonstrated a robust droplet fusion of two trains of droplets without fusion/sorting error. This was accomplished by the combination of the parallel droplet synchronization using a railroad-like channel and the manipulation of shape-dependent droplets using guiding tracks.

ACKNOWLEDGEMENTS

This work was supported by the National Science Foundation grants (Grant Nos. ECCS-1002255 and ECCS-0736501).

REFERENCES

1. Ahn, B., et al., Parallel synchronization of two trains of droplets using a railroad-like channel network. Lab on a Chip, 2011. 11(23): p. 3956-3962
2. Ahn, B., et al., Guiding, distribution, and storage of trains of shape-dependent droplets. Lab on a Chip, 2011. 11(22): p. 3915-3918.
3. M. T. Guo, A. Rotem, J. A. Heyman and D. A. Weitz, Droplet microfluidics for high-throughput biological assays, Lab Chip, 2012
4. Abbyad, P., et al., Rails and anchors: guiding and trapping droplet microreactors in two dimensions. Lab on a Chip, 2011. 11(5): p. 813-821.

CONTACT

*Kwang W. Oh, tel: +1-716-645-1025; kwangoh@buffalo.edu