DROPLET SYNCHRONIZATION OF TWO PARALLEL TRAINS OF DROPLETS USING A LADDER-LIKE CHANNEL NETWORK

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ABSTRACT

We present a reliable method of droplet synchronization in the microfluidic channel. Our approach does not need any active source (e.g., electric field) which can affect the samples in the droplets during the synchronization process. Moreover, the large quantity of droplets (droplet train) can be synchronized at the same time in a high-throughput manner. The droplet synchronization is achieved by the cross flow of the carrier oil due to the pressure difference between top and bottom channels.

KEYWORDS: Two-phase droplet, droplet synchronization, ladder-like channel network

INTRODUCTION

Droplet-based microfluidics involves the generation and manipulation of discrete droplets in microfluidic devices [1]. Monodispersed droplets can be thought of as single test sample, and merging two droplets containing different reagents is a necessary process in biological and chemical experiments [2]. To realize this process, perfect droplet pairing is an essential part. The proposed device does not need a paired or alternated droplet generator for the droplet synchronization. Moreover, the pre-formed and chemically or biologically treated droplets are available for the droplet synchronization as well as normal liquid or gas solution. In this research, we present a simple method for droplet synchronization of two trains of droplets using a ladder-like channel network. This device offers the synchronize droplets without any additional force in continuous flow system.

THEORY

Our device consists of a hydrodynamic flow focusing structure to generate two phase water-in-oil droplets and a ladder-like structure to synchronize droplets. Top and bottom channels were available to control individual flow rate independently and interconnected each other with a ladder-like channel network (Fig. 1a). The width of both top and bottom channel is 50 μm and the length between an adjacent interconnected channels is 120 μm. The width and length of the interconnected channels are 40 μm and 90 μm respectively. The height of the microfluidic channel is 50 μm uniformly. The interconnected channels have higher hydrodynamic resistance value than the main microfluidic channel ($R_i > R_c$, Fig. 1b) to prevent the cross flow of the generated droplets. Thus, the interconnected channels only allows the cross flow of the carrier oil between the top and bottom channels. Once the droplets enter the top and bottom channels, they cause the pressure difference between the top and bottom channels due to the phase difference ($\Delta \Omega$). So the volumetric flow of the carrier oil ($Q_{11}$) behind the leading droplet experience higher hydrodynamic resistance value than the equilibrium status, and it is divided into two flows: $Q_{12}$ and $\Delta Q_1$. Thus the velocity of the droplet in the top channel is slower compared to the initial velocity ($Q_{11} > Q_{12}$). In the contrast, the volumetric flow of the bottom channel ($Q_{22}$) is increased by $\Delta Q_1$ and hence results in a higher velocity of the droplet in the bottom channel. This velocity gradient makes it possible to diminish the phase difference ($\Delta \Omega$) and realize the droplet synchronization without any active sources. Finally, once the droplets are synchronized, the pressure difference ($\Delta \Omega$) between the top and bottom channel is diminished and cross flow of the carrier oil ($\Delta Q_1, \Delta Q_2, \Delta Q_3$) also disappears. And, the volumetric...
flow rate of the channel for the top and bottom channel are balanced \((Q_{14} = Q_{24})\).

**EXPERIMENTAL**

The device was fabricated using soft lithography to form microfluidic channels in polydimethylsiloxane (PDMS). To prepare the soft mold for the microfluidic channels, negative photoresist (MicroChem, SU-8 2050) was spin-coated and patterned on a silicon wafer. The channel height was 50 µm and the width was varied to control the hydrodynamic resistance value for each microfluidic channel. The PDMS mixture (Dow Corning, SYLGARD 184) were poured over the soft mold then cured at 80 °C for 1 hour, then followed by exposing O₂ plasma and was bonded with glass substrate. De-ionized (DI) water and HFE-7500 oil (3M) were used as aqueous and oil phases, respectively, and the ammonium carboxylate of Krytox 157 FSL (Dupont) was added into the HFE-7500 oil at 2 % by weight as a surfactant to prevent droplet coalescence.

**RESULTS AND DISCUSSION**

Our device was tested by varying flow rate for water \((Q_w)\) and oil \((Q_o)\) with different conditions (Table 1). For each case, we controlled \(Q_w\) and \(Q_o\) to make identical droplet length (size) and generation frequency for both top and bottom channels. For condition A, the length (size) of the generated droplets and the generation frequency were kept minimum. And, we increased the water flow rate \((Q_w)\) from 10 µl/hr to 50 µl/hr with fixed oil flow rate \((Q_o)\) 80 µl/hr to make longer droplets and high generation frequency. As expected, as \(Q_w\) was increased, both droplet length and generation frequency were increased (Fig. 2a). We defined synchronization efficiency as the number of matched droplets over the total number of generated droplets. The efficiency was plotted with each condition (Fig. 2b). For the flow rate condition C, although the droplet generation condition was the same, it resulted in the lowest synchronization efficiency among the conditions listed in Table 1. We are suspicious that the droplet generation process was not stable for the time being when we performed the experiment for the condition C, and the resulted droplet generation frequency in the top channel was not matched closely to that in the bottom channel due to potential

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**Table 1: Flow rate condition for both top and bottom channels (same droplet size and generation frequency).**

<table>
<thead>
<tr>
<th>Flow rate condition</th>
<th>A</th>
<th>Bottom</th>
<th>A</th>
<th>Bottom</th>
<th>A</th>
<th>Bottom</th>
<th>A</th>
<th>Bottom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aqueous phase flow rate (µl/hr)</td>
<td>10</td>
<td>10</td>
<td>15</td>
<td>15</td>
<td>20</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil phase flow rate (µl/hr)</td>
<td>80</td>
<td>D</td>
<td>80</td>
<td>E</td>
<td>80</td>
<td>F</td>
<td>80</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 2** (a) The length of droplet vs. generation frequency. (b) Droplet synchronization efficiency vs. generation frequency.

**Fig. 3** Photographs of droplet synchronization with different flow rate conditions from Table 1. Once two droplets are in the ladder-like channel network, phase difference diminishes due to the cross flow of carrier oil.

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experimental errors generated by syringe pumps, fluidic interconnection, partial pressure build-up, etc. As long as the generation frequencies are matched, the synchronization efficiency is close to 95%. Fig. 3 shows each experiment result listed in Table 1. Table 2 shows another flow rate conditions to generate two trains of droplets with a generation frequency difference (Δf) while each droplet length was maintained the same (~100 μm) (Fig. 4a). The synchronization efficiency was decreased with increased generation frequency difference (Fig. 4b). In specific plug-shaped conditions, one-to-multiple droplet synchronization was possible (Fig. 5). When the droplet length for the bottom channel was half of that for the top channel, but the generation frequency for bottom channel was twice of that for the top channel, two droplets in the bottom channel acted as a large single droplet (plug), thus realizing one-to-two synchronization (Fig. 5b). We also demonstrate one-to-three droplet synchronization (Fig. 5c).

**CONCLUSION**

We have designed and demonstrated a simple droplet-based microfluidic device for robust droplet synchronization/pairing. We could successfully synchronize two trains of droplets by adopting a ladder-like channel network. With matched droplet generation frequency, high synchronization efficiency was achieved up to 95%. Furthermore, we could demonstrate one-to-multiple droplet synchronization. This device will be very useful for droplet-based microfluidic applications, where perfect droplet pairing or synchronization is vital.

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**REFERENCES**


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