Microfluidic Manipulation in Lab-chips Using Electrorheological Fluid

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ABSTRACT: Microfluidic manipulation is one of the main concerns in lab-chip society. This article presents the design, fabrication and testing methodologies of electrorheological (ER) fluid-controlled active microfluidics chips. All of the fundamental building blocks, such as microvalves, micropumps and micromixers, are fabricated with similar processes in PDMS-based chips for easy integration. Such building blocks can be digitally controlled by on–off switching of electric fields applied on the parallel electrodes along the ER fluid channels. Experimental results show reliable functionalities of these devices. The ER active control scheme supplies additional flexibilities over the passive control of microfluidics. A hybrid approach of active mixers, combining the ER active actuation with the passive baffle structures, was applied to achieve more efficient chaotic mixing than the passive mixers available.

Key Words: electrorheological fluid (ER), MEMS, microfluidics.

INTRODUCTION

MICROFLUIDIC components play important roles in micro total analysis system or lab-on-a-chip systems that are widely used in DNA sequencing, drug screening and delivery, in situ monitoring and the other biotechnology and environment areas. Micro valves, mixers and pumps are fundamental building blocks to manipulate micro flows. Various kinds of active schemes were developed in recent years (Yang et al., 2000; Eddington and Beebe, 2004; Unger et al., 2000). In most of the designs with moving parts, diaphragms or cantilevers were adopted to control the flows. Polydimethylsiloxane (PDMS) based microdevices were intensively developed due to their flexibility, easy fabrication using soft lithography and bio-compatibility. These devices are pneumatically controlled, mechanically controlled or actuated by hydrogel. But an integrable and electronically addressable active control with fast response in milliseconds is still needed in micro total analysis systems.

Electrorheological (ER) fluid, as a well-known smart material, has been studied for many years, and was used in various engineering applications such as clutch, vibration damper, or valves. A kind of giant electrorheological (GER) fluid reported by Wen et al. (2003) can reach a yield stress as high as 200 kPa. The GER fluid consists of urea-coated 20 nm-diameter nanoparticles (barium titanyl oxalate) suspended in insulating oil. The transformation from liquid-like to solid-like behavior is relatively quick, on the order of 1–10 ms, and reversible. Such electric-field controlled rheological property implies a promising application for controlling micro flows.

This article reports a new methodology of microfluidic control with ER fluid, as well as the design, fabrication and testing of ER active chips. Micro valves, pumps, and mixing channels can be integrated into a single ER controlled lab-chip.

DESIGN METHODOLOGY AND EXPERIMENT OF ER ACTIVE MICROFLUIDIC ELEMENTS

ER fluid, as a kind of colloidal suspension, can sustain high shear stress when it is subjected to an external electric field. Such property was used in the designing of ER controlled microfluidic chip. Figure 1 shows the side view of an ER controlled chip and the associated ER circle system. The micro chip was made of PDMS by soft lithography (Xia and Whitesides, 1998). Two kinds of liquid channels: ER fluid channel and experimental fluid channel were arranged on different layers and be separated by thin diaphragms at the intersection areas. The ER fluid was circulated through the chip with a tubing pump (Masterflex C/L© used in the experiment) as labeled P in Figure 1.

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To stabilize the pressure difference between the inlet and outlet of the ER fluid channel, two reservoirs were connected on the both side of the pump, R_H dictates the reservoir with high pressure, and R_L dictates the reservoir with low pressure.

The basic working principle of the ER-fluid-control is a push-and-pull actuation of the flexible diaphragm sandwiched between the ER channel and flow channel when an on–off voltage is applied to ER fluid. Two pairs of parallel electrodes are arranged along each ER channel forming an upstream valve and a downstream valve for ER fluid itself. An electric circuit was designed to output square wave DC voltage signals to the electrodes. If an adequate DC electric field is added to the electrodes, the flow of ER fluid can be slowed or fully stopped due to the ER effect. The pressure in the ER channel between the two valves can therefore be modulated if the two valves are alternately opened and closed. Such a pressure change within ER channel will eventually result in the deformation of the flexible diaphragm with a vertical pull-and-push movement. Therefore, the liquid flow in the flow channel will be controlled with the pressure change in ER channel. This push-and-pull mechanism has the advantage of faster response time compared with valves with only a push source, because the PDMS diaphragm has a low Young's modulus and cannot resume its original position very quickly by its own elasticity. The movement of the diaphragm can be digitally controlled on its amplitude, frequency, and phase by electric signals.

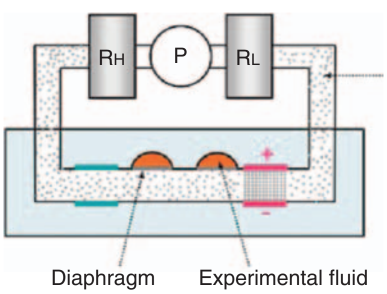

Figure 1. *Schematic diagram of the electrorheologically controlled microfluidic chips and the ER circulation system; the diaphragm between the ER fluid channel and the experimental fluid channel can be pushed up and pulled down.*

ER active valves, pumps and mixers can be achieved in a similar working principle as shown in Figure 1. In Figure 2(a), a micro valve is formed by simply overlapping perpendicular the ER fluid channel layer on a micro fluidic channel layer (Niu et al., 2005). The flow channel was molded out with rounded photoresist mold, by hard-baking of the channel mold after photolithography, to assure the flow can be fully closed (Unger et al., 2000). It is tested that the response time of on–off switching of the flow can be <10 ms and with sound reliability, suitable for most microfluidic applications. It should be noted that the diaphragm area can not be too big in the valve chips to avoid fluctuation of flow speed. But if the diaphragm area is enlarged intentionally, large amount of liquid can be repelled and imbibed, therefore the diaphragms can be used as pulsating pumps, for example, in active pumps or mixers, as shown in Figure 2(b) and (c).

By arranging three pulsating pumps serially on a micro flow channel, an ER micro pump was fabricated as show in Figure 2(b) (Liu et al., 2006). The co-operative movements of the diaphragms actuated by the ER fluid valves are the direct driving mechanism for pumping, As the electrodes can be independently controlled, we are able to digitalize the signals so that the voltages are expressed and managed with binary codes. Besides the tunable voltages, digitized programmable control offers flexibility (e.g., reversing the pumping flow direction) and adjustable individual action steps. It was tested that the pumped flux reaches a peak of 1.4 μl/s at ~35 Hz (in a testing range of 0–100 Hz) when all the electric signals have the strength of 2 kV/mm.

Microfluidic mixer is not only a critical component in lab-on-a-chip but also of interest in fundamental physics because in microscale systems only creeping flows can exist due to the small Reynolds number. It was numerically shown that chaotic mixing can occur in the orthogonal-channel pulsating mixers (Niu and Lee, 2003). However, an active chaotic mixer chip integrable with the other component is not an easy task due to the difficulties in the fabrication and operation in microscale. Using an ER controlled mixer (Niu et al., 2006a) as shown in Figure 2(c), we have experimentally demonstrated that fully chaotic mixing can really be achieved.

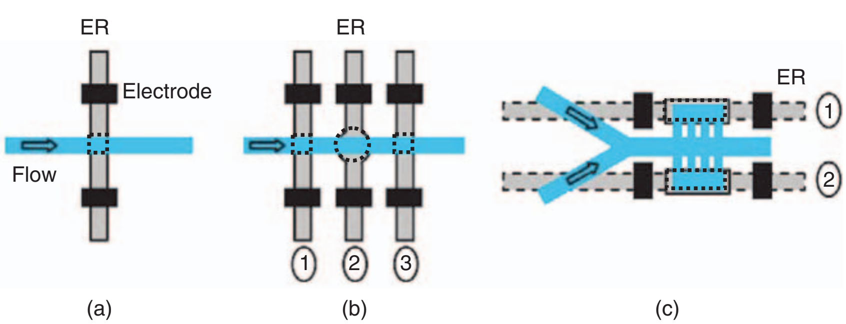

Figure 2. *Schematic diagram of the electrorheologically controlled microfluidic chips: (a) microvalve; (b) micro pump; (c) micro mixer. The actuation areas are marked with dashed lines.*

In the mixer chip, the two pulsating pumps were set to operate in a contrast phase. Amplitude and frequency were adjusted to achieve optimal mixing depending on the flow speed at the inlet.

HYBRID APPROACHED OF ER ACTIVE MIXERS

The digitally addressable ER active control offers more flexibility over the passive ways of microfluidic manipulations. Moreover, if these two approaches can be combined together, better or new functionalities can be induced. For example, in the active mixers proposed by Hong et al. (2004), five active elements are needed to finish one process of mixing/reaction. By using the active mixer in part 2, a continuous mixing directly in the fluid channel can be achieved with only two active elements. But during the optimization of the control parameters, it was found that the actuation amplitude of the pulsating pumps should be increased proportionally with the increase of flow speed at the inlet, and there exist a optimal frequency range, out of which the mixing is poor and most of the ER pumping energy was wasted in the driving of the unmixed liquid blobs back and forth in the orthogonal side channels.

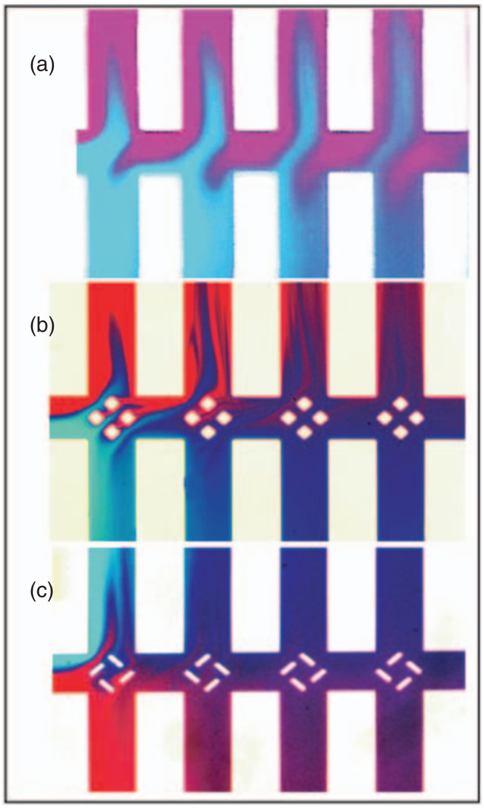

Figure 3. *Hybrid approach on chaotic mixing. Comparison of the three kinds of mixing channels in the same control parameters. (a) In the channel without baffles, regular blobs (Niu and Lee, 2003) exist; (b) In the channel with symmetric baffles, regular blobs are cut into thin layers that chaotic mixing can be achieved; (c) In the channel with asymmetric baffles, KAM blobs disappear more rapidly and stronger chaotic mixing can be achieved.*

Based on a Poincaré section analysis and its physical understanding, different passive flow baffles were installed in the main microfluidic channel to enhance mixing at high frequencies (Niu et al., 2006b). Results shown in Figure 3 indicate that the combined hybrid approach enables effective chaotic mixing at enhanced frequency and reduced passage distance in two-dimensional flows. Under the same ER control parameters but using asymmetric baffles, regular blobs shown in Figure 3(a) was found to disappear in Figure 3(b) and (c). Therefore, the hybrid mixer does improve the mixing efficiency over the simple model proposed by Niu and Lee (2003).

A continuous micro mixer chip, including three valves and one mixer, was further proposed as shown in Figure 4(a). The valves operate in the same manner as in ref (Niu et al., 2005). But the working fluidic channel was further improved to avoid dead end at the pump areas for easy operation, and the working fluid can flow through the pump areas as indicated by the white arrows in Figure 4(a). During the alternating pumping, working fluid can be stretched, folded, splitted, and recombined in the channels. Figure 4(b) shows that fully mixing can be achieved even after four pairs of side channels. By switching the microvalves, different streams of liquid can be mixed optionally.

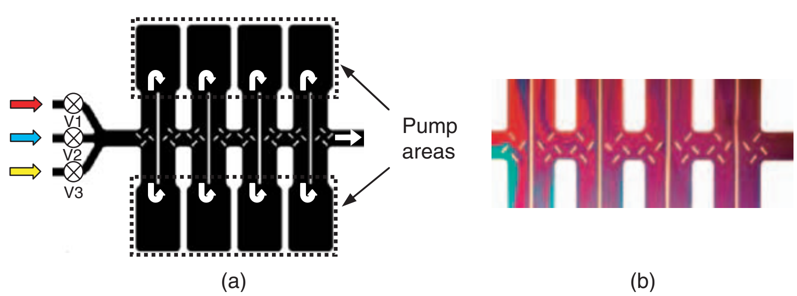

Figure 4. *A continuous micromixer that can mix different streams of liquids, in a mechanism of splitting and recombination of the flows as well as chaotic mixing. (a) Schematic picture showing the continuous micromixer design. V1, V2, and V3 indicate three ER valves. (b) Optical image of the mixing channel with ER perturbations.*

CONCLUSIONS

A new kind of active microfluidic actuation-ER fluid control is introduced in this article, with specific details of design, fabrication and testing on the building blocks such as ER valve, pump, and mixers. Such chips and the future large scale integration may find applications in microfluidic control, chemical reactions and so on.

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