Active microfluidic mixer chip

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We report the design and fabrication of a chaotic mixer based on the electrorheological (ER) fluid-controlled valves. The flow in the main channel is perturbed by liquid flow in orthogonal side channels, driven by hydrodynamic pulsating pumps. Each pulsating pump consists of a chamber with diaphragm plus two out-of-phase ER valves operating in a push-pull mode. All the valves, pumps, and mixing channels are integrated in one polydimethylsioxane chip. Mixing characteristics in the main channel are controlled by the strength and frequency of external electric fields applied on the ER fluid. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2195567]

Microfluidic mixer is not only a critical component in laboratory 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.[1–3] Efficient chaotic mixing to realize fully mixed liquid phases has received much study in recent decades. It was observed that chaotic flows may occur in some simple two-dimensional (2D) unsteady flows[4–6] and three-dimensional (3D) flows,[7–11] leading to incessant stretching and folding of the liquid elements so that the striation thickness of liquid blobs decreases exponentially with time/distance. However, achieving a homogeneous and rapid mixing for the entire channel of flowing liquids is still not trivial because there can be regular, unmixed areas of various sizes, i.e., regular Kolmogorov-Arnold-Moser (KAM) holes or tubes, even in the chaotic regions.[3,12] At present there are two mixing approaches: one is the *passive mixer* in which the flow field perturbations are caused by geometric obstacles,[7–11] and the other is the *active mixer* in which an external energy source is employed to perturb the flow field, either in the form of mechanical pulsation[4–6] or electrokinetic forces.[13,14] Active mixers can have versatile functionalities because parameters such as perturbation frequency, phase, and amplitude can all be adjusted during the operation, thereby enabling fully chaotic mixing in the full range of Reynolds numbers generally encountered in microfluidic applications. However, only a few investigations for active chaotic mixing have been reported due to the complexity of control schemes and difficulty in fabrication—especially in the microscale. As one type of active mixers, orthogonal-channel pulsating micromixers[4–6] have demonstrated chaotic mixing in simple 3D structures by disrupting the primary flow with cross-stream secondary flows. But active mixers that have been studied so far have the disadvantage of requiring external valve control systems that cannot be fully integrated on a chip.

We present a design and implementation methodology to realize fully chaotic mixing, based on valves that are controlled by a "smart material"—electrorheological (ER) fluid. These valves operate through the electric field-induced strength variation of the ER fluid, with very rapid response. In our microfluidic mixer the micro valves and pumps can be integrated with other components, thus offering a route to laboratory-on a chip with digital control.

An important element of our mixer is the ER fluid, sometimes also known as a smart material. Recently, a giant electrorheological (GER) fluid with the yield stress more than 200 kPa was developed.[15] For such GER fluid, the transformation from liquidlike to solidlike behavior is relatively quick, on the order of milliseconds, and reversible. Therefore, it can provide simple and fast-response interfaces between electrical controls and mechanical systems, offering promising potential for applications in microfluidic devices, such as microvalves.[16]

Our design for microfluidic mixer chip is shown in Fig. 1(a), consisting of four polydimethylsioxane (PDMS) layers fabricated using the soft lithography techniques.[17] Fluids mixing channel and ER fluid control channel are located on layers I and III, respectively. The ER fluid channel (200 μm deep and 400 μm wide) with two branches is connected to two ER fluid reservoirs with inlet and outlet tubes. A pressure differential is established between the two reservoirs so as to enable the flow of the ER fluid. Two pairs of electrodes (on layers II and IV) are located along each branch of the ER channels. The ER flow can be slowed or stopped if adequate dc electric field is applied on any pair of the electrodes due to the electrorheological effect—coalescing of the nanoparticles into chains along the direction of electric field (orthogonal to the flowing direction). dc electric field signals on these two pairs of electrodes are in the form of two square-wave pulses with opposite phases, leading to a pressure condition in the ER channel between the two pairs of electrodes that alternates with time. Such pressure variation can be transferred to the control reservoirs at the end of each side channels in layer I, through a 40 μm thick PDMS diaphragm in layer II. A pulsating pump is thereby formed in each ER channel branch, in which the force acting on the control reservoirs (through diaphragm deformation) can be adjusted via applied electric field strength and frequency. It should be pointed here that the ER fluid used was filtered before testing in order to get rid of large particle agglomerations from ER fluid fabrication. During operation, the ER fluid is circulated continuously through the chip by the pump; possible sedimentation is thereby avoided. All of the chip layers are PDMS based and being permanent bonded after oxygen plasma treatment. Such a mixer chip is very reliable during hours of experiment and repeated testing for several months.

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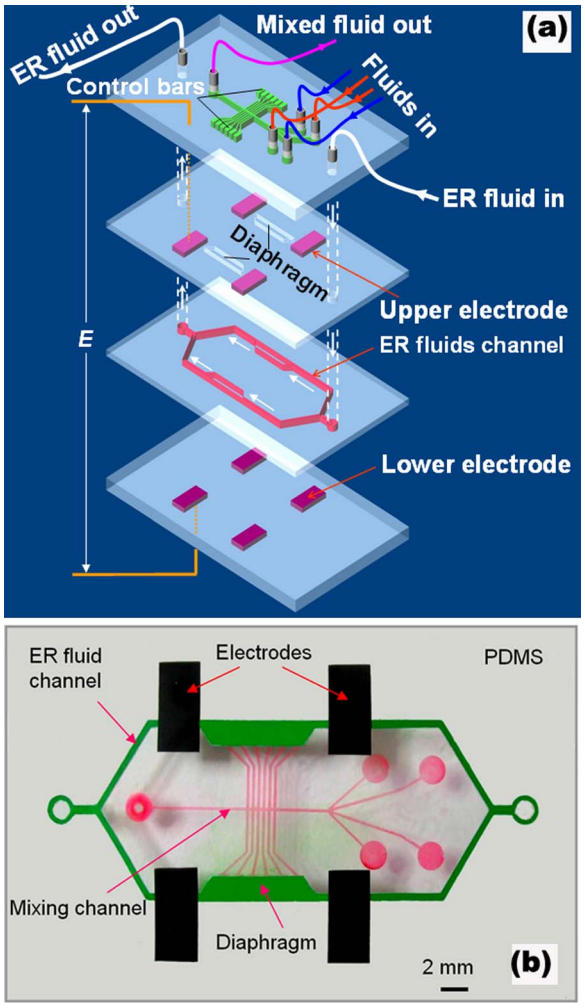

FIG. 1. (Color online) (a) Schematic picture showing the PDMS active mixer design and construction. Layer I is the mixing channel layer. Layer II is the thin membrane layer. Layer III is the ER fluid channel layer. Layer IV is the cover layer. Parallel electrodes are located on layers II and IV. (b) A photographic image of the micromixer chip.

The fluid mixing channels (both the main channel and the orthogonal side channels) are 38 μm in depth and $L=200$ μm in width. Each of the six pairs of orthogonal side channels is separated by 200 μm from the neighboring pair. The two pulsating pumps are controlled to have the same amplitude but opposite phase. Therefore a periodic parabolic cross-stream secondary flow, (with differential equation $\dot{y}=\nu_p[1-(2x/L)^2]\sin(\omega t)$ to describe the movement of the fluid particle, ν_p being the perturbation amplitude and ω the angular frequency) can be established in the side channels to disrupt the parabolic primary flow ($\dot{x}=\nu_0[1-(2y/L)^2]$, ν_0 being the initial flow velocity of the fluid in the main channel, at the point where the main channel intersects the first side channel) in the main channel, with the aim of achieving total mixing. This design is similar to that proposed by Volpert,[4] but in our case, the frequency, phase, and amplitude of perturbations in all the side channels are the same for easy fabrication and control. Mixers with such a control strategy have demonstrated fully chaotic mixing in numerical simulations.[5] An image of the microchip is shown in Fig. 1(b).

In our experiments, we choose the perturbation amplitude ($A_p=\nu_p/\nu_0$) and frequency (ω in rad/s) in the side channels as the main parameters to study chaotic mixing behavior. These two parameters are related directly to the electric field strength (E) and frequency of the control dc electric field applied to the ER fluid. Calibrations of this relationship were carried out by varying one parameter while keeping the other one constant. Figure 2 illustrates our experimental setup for calibration and mixing experiments. GER fluid of 30%–40% was pushed in and pulled out of the ER channel with a pump (Masterflex), with a relatively low control voltage (less than 1600 V/mm) applied between the electrodes. The outer pressure sources of the ER fluid were kept constant during testing, approximately +10 psi for the pressure source and −10 psi for the vacuum source relative to 1 atm. A specifically designed voltage control box is used to control dc signals. Measurements of mixing in the channels were carried out on an Olympus SZ-STU2 microscope with Sony color video camera. We measured perturbation amplitude A_p in the side channels as a function of E and ω by using particle tracking (1.5 μm polystyrene particles). It is found that A_p decreases quadratically with ω at fixed electric field [see Fig. 3(a)], while it increases exponentially with applied electric field [see Fig. 3(b)]. Particle tracking results also indicate that the amplitude is approximately sinusoidal in the frequency range ($\omega>1$) shown in Fig. 3. Therefore the perturbations in the side channels can be described as $A_p[1-(2x/L)^2]\sin(\omega t)$.

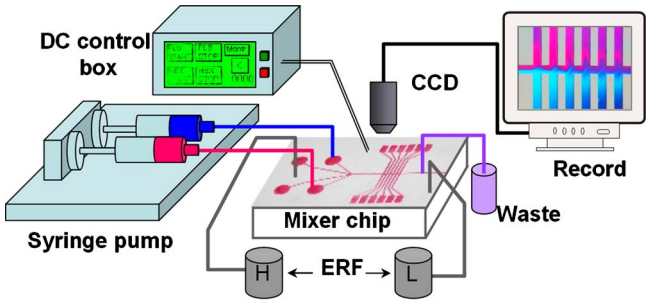

FIG. 2. (Color online) A schematic picture illustrating the experimental setup.

The working fluids, blue and red inks in 50 wt% sucrose water solution (with measured viscosity of 0.013 kg/m s and

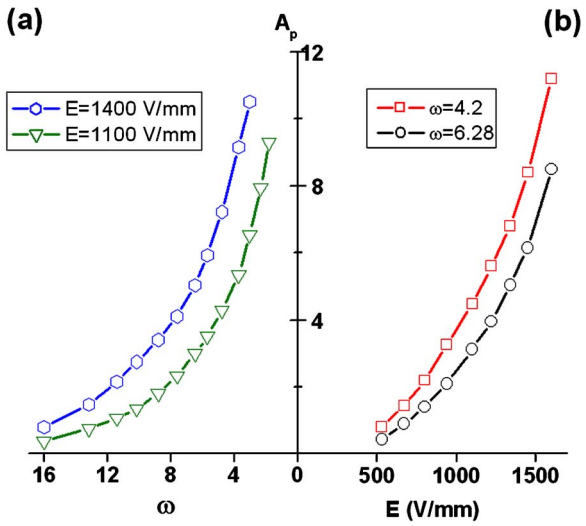

FIG. 3. (Color online) (a) Perturbation amplitude of the cross-stream secondary flow plotted vs frequency for two values of the applied electric field. (b) Perturbation amplitude plotted vs electric field for two different frequencies.

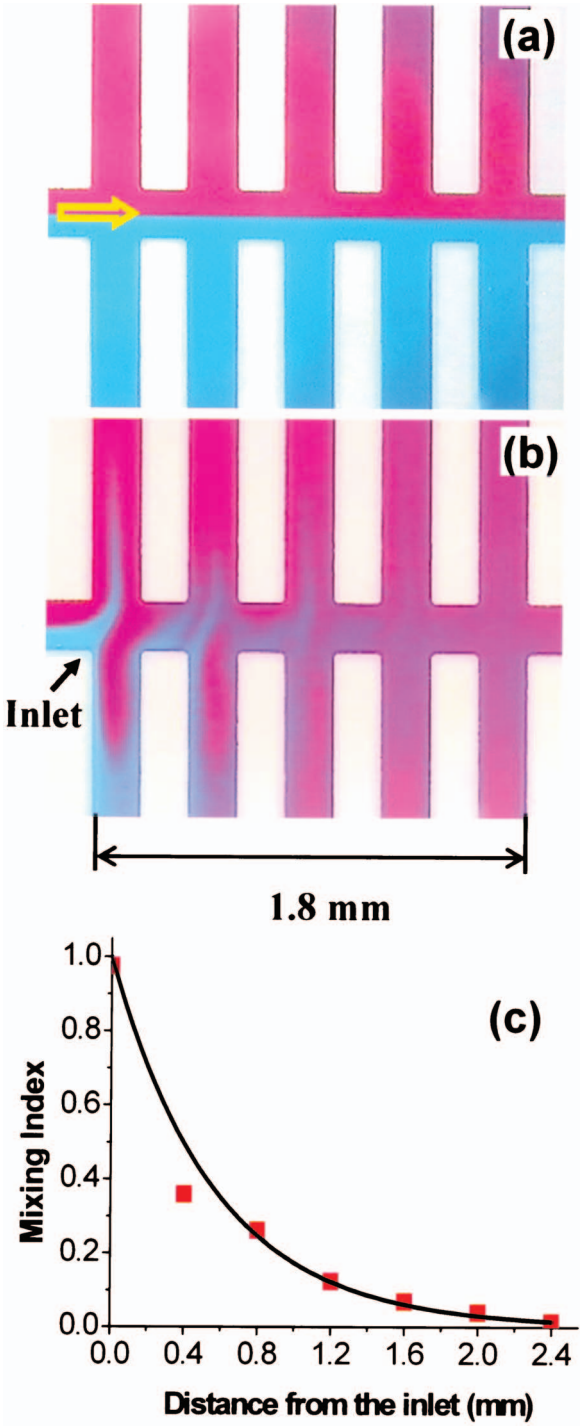

FIG. 4. (Color) (a) Optical image of the mixing channel without perturbation. There is no discernable mixing between the two streams of colored liquid. (b) Fully chaotic mixing at $A_p=4$ and $\omega=4.2$. There is no discernable color blob even after five pairs of side channels and the two streams can be fully mixed in a channel length less than 1.8 mm. (c) Mixing index for slices of the main channel flow in (b), plotted as a function of distance unit. The distance unit is defined to be the center-to-center separation of the two neighboring pairs of side channels, 400 μm.

diffusion constant of the dye $D=3.12\times10^{-11}\mathrm{m}^2/\mathrm{s}$), were injected into mixing channels by a (KD Scientific) syringe pump (see Fig. 2) with a flow rate $v_0=200$ μm/s.

When there is no applied electric field, i.e., no secondary flow perturbation, only Poiseulle flow exists in the main channel, with weak attached Hele-Shaw flow in the side channels close to the intersection areas. The two different-colored liquids (red and blue) flowed separately. Only molecular diffusion across the interface can be observed, as shown in Fig. 4(a). The amplitude A_p of the secondary cross-stream flow was gradually increased by increasing E while fixing the frequency ω of the electric field at 4.2. When $A_p\sim0.35$, the system was only partly chaotic. When A_p was increased above 1, the interface line was stretched and folded intensively and there is no discernable ink blob existing after a distance of 1.8 mm when $A_p\approx4$ as can be seen in Fig. 4(b).

To assess the homogeneity of mixing along the main channel, we have experimentally evaluated the mixing index $M_i=(1/\bar{c})\sqrt{\Sigma(c_j-\bar{c})^2/N}$, by collecting the concentration c of the dyes in the slices of main channel (as captured by the video picture frames), downstream from each pairs of side channels, where $\bar{c}$ is the mean concentration of the mixed dye solution and N is the total number of pixels. Because the movement of fluid element in the channel is time dependent, all the picture frames in one period of perturbation were evaluated. The mixing index is found to follow the exponential law [Fig. 4(c)] $M_i\propto\exp(-\lambda t^*)$, where $t^*=(P_{\mathrm{itch}}/v_0)t$, $\lambda\approx0.35$ is the Lyapunov exponent, and $P_{\mathrm{itch}}=400$ μm. This behavior is consistent with that predicted by theory and numerical analysis.[5] Thus we have experimentally demonstrated that fully chaotic mixing can be achieved in ER-controlled mixer. For higher flow velocity v_0, fully chaotic mixing can also be observed by increasing ω and A_p proportionally. But for a fixed v_0, there exists an optimal region of ω and A_p for fully chaotic mixing, with higher ω or lower A_p inducing less effective mixing.

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