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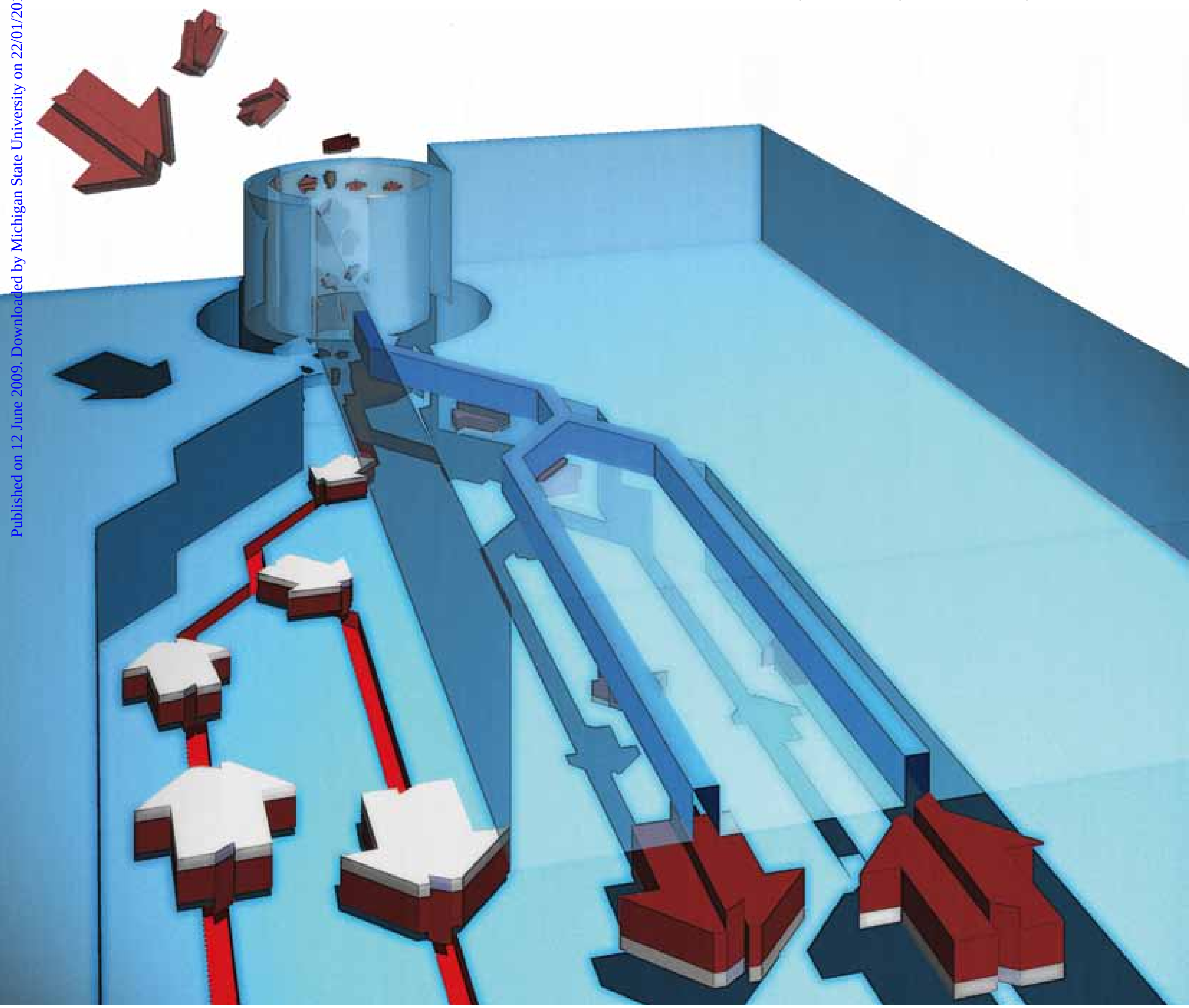

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Sorting directionally oriented microstructures using railed microfluidics

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We demonstrate the microfluidic sorting of directionally oriented (anisotropic) microstructures by their orientational state in solution using the concept of railed microfluidics. After being injected into a microfluidic channel, the microstructures rotate and flip in various directions. In order to sort microstructures in an organized way, we designed the microstructures and the microchannel to allow for orientation-based control of microstructure movement. In order to sort microstructures based on their rotation, we used a wedge shaped fin on the microstructures and a Y-shaped railed microfluidic channel. For sorting flipped particles, we use a double-railed microfluidic channel that has grooves on both its top and bottom surfaces. By integrating the two sorting methods we demonstrated high throughput, autonomous sorting into four different orientational states: unrotated–unflipped, rotated–unflipped, unrotated–flipped, and rotated–flipped. Here we not only demonstrate orientational assembly of directionally dependent microstructures, but also present design considerations for future work.

Introduction

In bottom-up fabrication schemes building blocks are first fabricated and then assembled together to form a larger super-block structures. As the size of building blocks gets smaller, and the number of components gets larger, the conventional serial assembly methods such as robotic pick-and-place assembly becomes delicate and expensive. Self-assembly is attractive at the micro-scale because the assembly process is achieved in a parallel autonomous manner.[1–3] Various fluidic self-assembly methods have been applied as assembly mechanisms for various on-chip devices. For example, LED (light emitting diodes),[4,5] RF-tag components,[6] FET (field-effect transistors)[7] and other small components[8,9] have been assembled on a chip using fluidic self-assembly.[10]

Fluidic self-assembly of isotropic components (having homogeneity in directions) such as colloidal particles, has been extensively investigated. Various assembly and patterning strategies have been developed to form 2D, 3D arrays on a substrate or thin films.[11–14] In these assemblies, the shape of particles are mostly limited to having a spherical shape since particles are chemically synthesized using emulsion. Therefore, the control of particle orientation is not very important in self-assembly of isotropic components into simple periodic colloidal crystals.

Recent advancement in lithographic fabrication of free floating particles such as continuous flow,[15] stop flow[16] and optofluidic maskless lithography[17] added great flexibility in the control of shape and composition of components. In these lithography techniques particle shape can be freely controlled using mask patterns. This allows for easy production of anisotropic particles in a microfluidic channel. Self-assembly of anisotropic particles can allow for the creation of complex structures.[18–22] For example, these microstructures can include a mechanical latch structure so that they can be mechanically assembled. In assembling of these anisotropic particles, orientation is especially important.

For high level assembly of particles formed using these fluidic lithographies, we have developed an assembly technology based on railed microfluidics. Compared with conventional fluidic self-assembly which relies on probabilistic shape matching, railed microfluidics enables deterministic assembly of complex heterogeneous microstructures based on the concept of guiding microstructures on grooved microfluidic channels.[23] Designing the groove can allow for deterministic control of the movement of the microstructure so that high yield and throughput of assembly are achieved.

In this assembly approach based on railed microfluidics, multiple components are prefabricated at the fabrication site, such as on a wafer or in a microfluidic channel in advance of the assembly operation. After prefabrication of heterogeneous microstructures the structures must be gathered and injected into the microfluidic channel for assembly. Our method allows for two dimensional sorting of microstructures, a strategy that is potentially useful for many assembly applications where the flip or direction of the microstructure is meaningful.

However, when injecting prefabricated microstructures made elsewhere into a microfluidic channel using pipetting, the particles randomly float in a buffer solution and are disordered at the inlet of the microfluidic channel in which they are to be assembled (Fig.1a). The prefabricated particles can be rotated and flipped as shown in Fig. 1b. Thus, for the fluidic assembly of these prefabricated particles, an autonomous method of sorting, according to orientation, could potentially be very useful.

In this paper, we demonstrate completely autonomous sorting of prefabricated microstructures by their orientational state using the concept of railed microfluidics. We propose two sorting methods for rotation and flip of the particles in solution. First, a wedged fin on the microstructure and a Y-shaped railed

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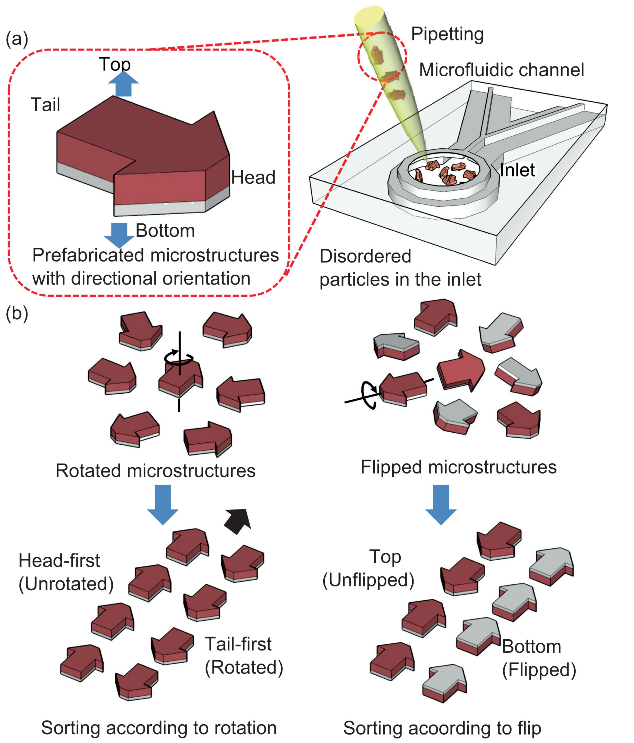

Fig. 1 Motivation for sorting directionally oriented microstructures for the injection process (a) Free-floating microstructures are disordered in the inlet. (b) The directionally oriented microstructure has four orientations. (unflipped or flipped, head first or tail first).

microfluidic channel are demonstrated to sort out rotated particles in solution. Second, a double railed microfluidic channel is proposed to sort out flipped particles in solution. We implement the two sorting methods in a microfluidic channel and demonstrated high throughput, autonomous sorting by separating the microstructures into four different orientational states: unrotated–unflipped, rotated–unflipped, unrotated–flipped, and rotated–flipped. Finally, we demonstrate sorting using a micro-latch system and design considerations for the production of the particles and sorting channels are presented.

Results and discussion

When attempting to fluidically assemble prefabricated directionally oriented particles into a highly ordered complex structure in a microfluidic channel, particle orientation is very important. However it's an obvious challenge given that microstructures float freely in random orientations after they are injected into a microfluidic channel as seen in Fig. 1b.

Sorting of rotated microstructures

In order to fluidically separate the microstructures according to their head-first or tail-first orientation, we apply the railed microfluidic concept and a directional control scheme using a Y-shaped branch rail and wedged fin on the microstructure (Fig. 2). When the finned microstructures go into the channel it encounters a Y-branch point where particles are separated into the two

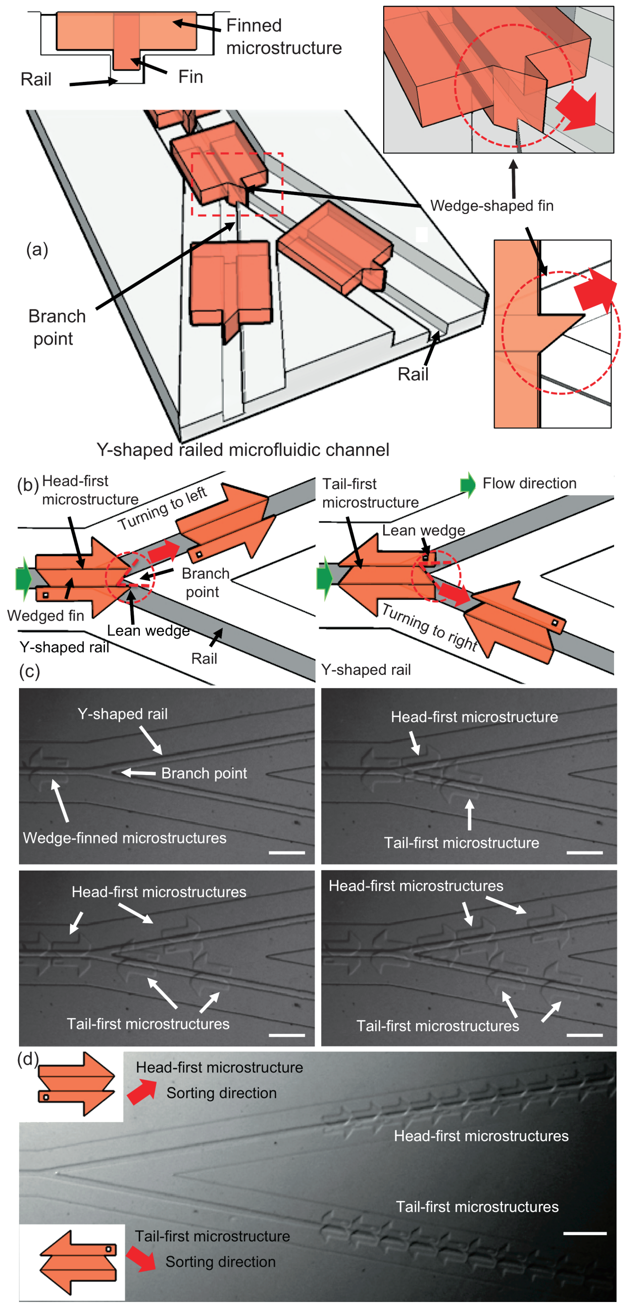

Fig. 2 Sorting schematic diagram based on direction control using a wedged fin and a Y-shaped railed microfluidic channel. (a) Design of wedged fin at head and tail of an arrow-shaped microstructure. (b) Direction control using wedged fin and Y-shaped groove (head-first: turning left, tail-first: turning right). (c) Sequential images of sorting the microstructures with respect to rotation. (d) Successfully sorted microstructures according to the orientation (head first and tail first) Scale bar: 100 μm.

branches at an equal rate based on the shape of the wedge with respect to the branch.

When the wedge fin on the microstructure contacts a branch point of the rail, the tip of the wedge fin on the microstructure enters into one of the branches. The microstructure slips into the branch along the same slope of the wedge as shown in Fig. 2a. In this setup, the direction of the particle's movement at the Y-shaped rail is controlled by the shape of the wedge. We designed an arrow-shaped finned microstructure including two wedges at the head and tail as shown in Fig. 2b. Because the shape of the wedge determines the direction of the particle's movement at the Y-branch point, the wedges are oppositely designed at their head and tail, so they are separated into different rails. For example, the wedge at the head is designed to turn left and the wedge at tail is intended to turn right when they meet the branch point in the Y-shaped rail. Thus, the head first particle was designed to push the particle to the left channel and the tail first orientation designed to direct the particle to the right channel, allowing for the particle separation based on the head first or tail first orientation (Fig. 2b).

The microfluidic channels, including the Y-shaped rail channel, were fabricated with PDMS (polydimethylsiloxane) using soft-lithography replica molding. Two types of microstructures with two orientations (head first and tail first) were synthesized at the inlet channel by *in-situ* photo-polymerization. After fabricating these particles, pressure was applied into the microfluidic channel in order to automatically sort them. The microstructures were successfully sorted according to each orientation as shown in Fig. 2c and d.

Sorting of flipped microstructures

A fin on the microstructures was used to differentiate between its top and bottom, and to sort it accordingly. As shown in Fig. 3a, using a double rail scheme (a top rail and a bottom rail), we were able to guide one sided finned microstructures into different channels based on their flipped state. In order to allow for this, a groove (rail) was patterned on the top of a microfluidic channel and on the bottom. In the design, the two grooves on the top and the bottom are separated into two branches directed into different microchannels. When free-floating finned microstructures are loaded on the microchannel from the inlet, fin up microstructures enter into the microfluidic channel by guidance of the top rail and fin down microstructures are guided by the bottom rail. When the top and bottom grooves split off into two channels microstructures are sorted based on their flip state (Fig. 3b).

The double railed channels were fabricated by bonding two microfluidic channels. A square code on a finned microstructure was used as a mark in order to distinguish unflipped (fin-up) and flipped (fin-down) microstructures. By simply applying fluidic force into the microfluidic channel, unflipped microstructures and flipped microstructures were automatically sorted with respect to the flip status of their fin (Fig. 3c).

Sorting and assembly of prefabricated microstructures

After demonstrating the ability to sort microstructures based on their flip state (fin-up or fin-down) as well as sorting with respect to rotation (head first or tail first) we applied both concepts to sorting prefabricated microstructures, that include a latch component, for assembly. In the latch microstructure design the male component occupies the head and the female component makes up the tail. The shape of free floating microstructures in this assembly is shown in Fig. 4a. We prefabricated microlatches

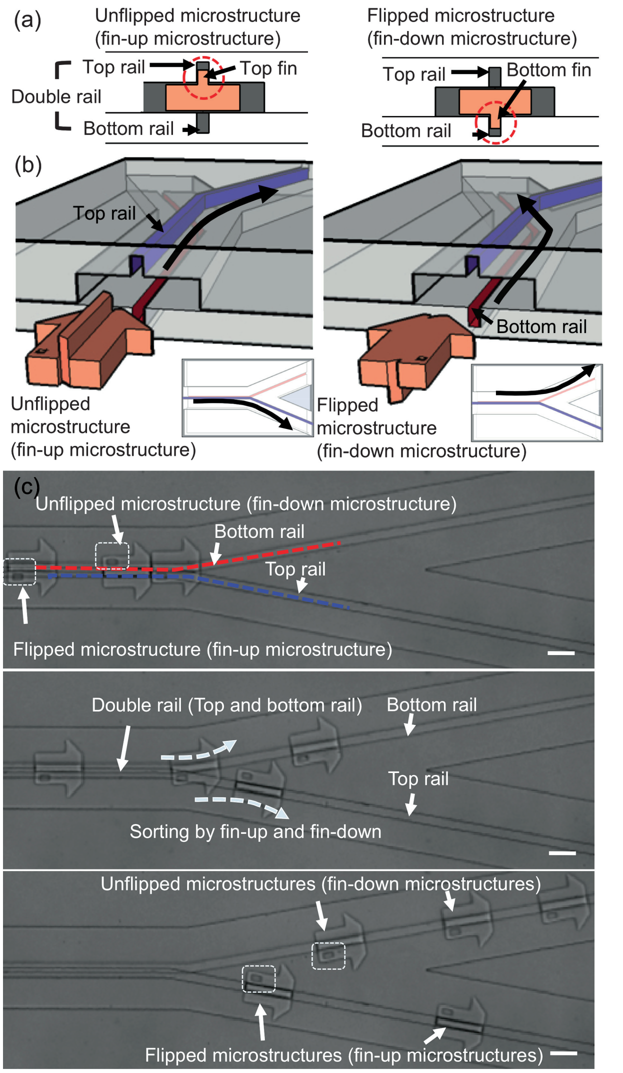

Fig. 3 A schematic diagram of a double rail system for sorting unflipped and flipped microstructures. (a) A cross-section of the microfluidic channel. An unflipped microstructure (fin-up microstructure) enters into the top rail. A flipped microstructure (fin-down microstructure) confined by bottom rail. (b) Double rails (top and bottom) are separated into two branches (top rail: blue, bottom rail: red). (c) The unflipped microstructure and the flipped microstructure move along the top rail (blue) and bottom rail (red), respectively. Scale bar: 100 μm.

in a railed microfluidic channel using stop-flow lithography[16] for high throughput fabrication. For the mechanical latching mechanism, we fabricated flexible latch beam by controlling UV dose, affecting flexibility. These prefabricated microstructures were gathered into a test tube. After massive fabrication of microlatches, we introduced these microstructures into the railed microfluidic channel with oligomer solution using a syringe pump. Creating microstructures outside the area in which they are assembled allows for the creation of particles made of various materials, thus increasing the breadth of applications. These include construction of heterogeneous microgel arrays' as well as silicon chip and flexible circuit assembly. In order to assemble the microlatches using the latch mechanism, the microlatches must be sorted according to orientation before fluidic assembly is

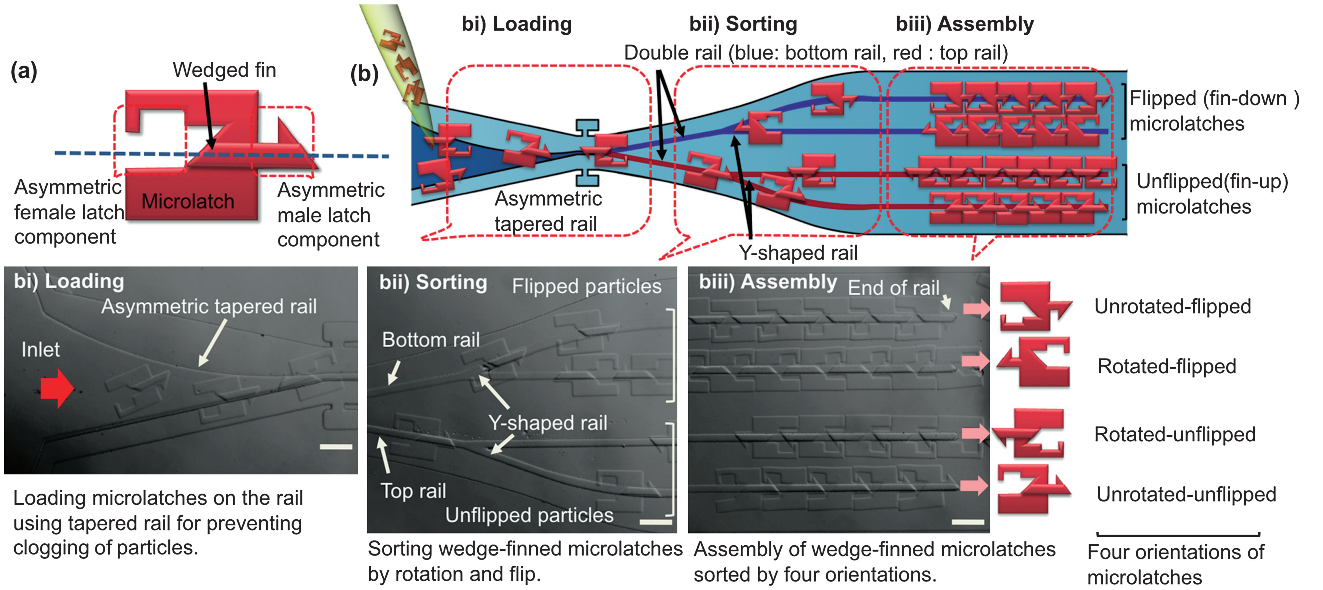

Fig. 4 Sorting and assembling prefabricated latch microstructures with two sorting methods (Double rail scheme, and wedged fin and Y-shaped rail). (a) A microlatch with an asymmetric male latch beam and an asymmetric female latch. (b) A schematic illustration of assembling prefabricated microlatches with directional orientation. The top rail (blue) for flipped (fin-down) microlatches and the bottom rail (red) for unflipped microlatches (scale bar: 100 μm). (b-i) Loading of prefabricated microlatches on the rail. (b-ii) Sorting of microlatches according to four orientations. (b-iii) Assembly of the microlatches at the end of the rail.

possible. Not only do the microlatches need to be lined up in the same head to tail orientation, but because the latch is asymmetric in two planes, they also need to have the same flip state in order to latch together. The simultaneous sorting mechanism, where microlatches are separated by rotation and flip is shown in Fig. 4b-ii.

Because the microlatches are not aligned with the railed microchannel, when they are injected into the microfluidic chip an asymmetric tapered microchannel is necessary for loading. The asymmetric tapered section of the channel makes the microstructure rotate because the flow stream is asymmetric in this area (Fig. 4b-i).

Although the tapered design was successful at aligning the microstructure so its fin could slide into the channel groove, clogging at the junction became a problem with a high concentration of microstructures. While having a high concentration is desirable as it relates to throughput, we were able to lower the concentration (10^4–10^5 microstructures/ml) to prevent clogging without significantly lowering yields. In this way, the two sorting methods described above were integrated on a microfluidic chip for perfect sorting and assembly of prefabricated microlatches with minimal clogging.

Design of Y-shaped rail and fin width

The width and length of a fin that can be successfully sorted with respect to its rotational orientation using Y-shaped rail branching, is determined by the width of the rail and the angle between the two branches. The rail needs to provide enough space for the fin to turn along one of the branches. The maximum width and length of the fin is related to the width of the of the rail (groove) onto which the fin is guided and the angle between Y-branches. For geometrical design of wedged fin applications, we assume that the fin and microchannel are rigid enough not to deform by fluidic force. We ignore the fin bending effect increasing maximum fin width and length. The maximum particle width that can be used in sorting microstructures using railed microfluidics (Fig. 5a), w_f is

$$w_f = d_B \sin\theta_f + \frac{w_R}{2}\cos\theta_f \qquad (1)$$

where θ_f is the rotation angle of fin from rail, w_R is the width of rail, and d_B is the branch point distance. The distance of the branch point distance represented by d_B is

$$d_B = w_R\left(\frac{1}{\sin\theta_B} - \frac{1}{2\tan\theta_B}\right) \qquad (2)$$

where θ_B is the angle between Y branches and w_R is the width of rail. The maximum rotation angle θ_f is

$$\sin\theta_f = \frac{\frac{1}{2}w_R}{L_t} \qquad (3)$$

Despite laminar flow characteristics inherent to microfluidics, if the fin is not long enough, it can rotate slightly at the Y-branch point, which can cause mis-sorting. The fin should be long enough so that the slope of the wedged fin should come into contact with the wedge of the rail before being sorted at the branch point. When the fin is rotated before the slope of wedge fin meets the wedge of the rail, the direction of sorting cannot be predicted. In this case the particle is sorted randomly by fluidic factors such as the difference of flow resistance between branches or asymmetric drag force at different vertical positions in the microchannel. Therefore the fin needs to rotate within a limited range in the Y-branch area so that the slope of its fin

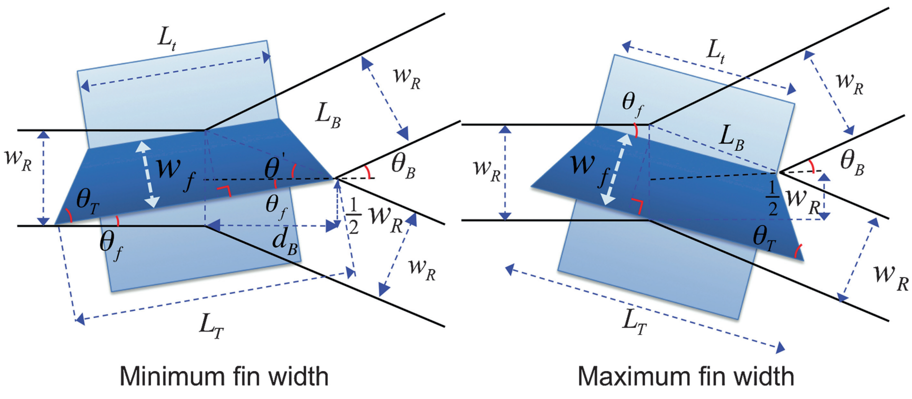

Fig. 5 Design approximation of maximum and minimum fin width (w_f) for sorting rotated microstructures with Y-shaped railed microfluidic channel (w_R: rail width, θ_B: Y-branch angle, L_T, L_t: fin lengths, θ_T: fin angle, d_B: branch point distance). A fin size larger than the minimum width and length can be perfectly sorted without error, such as misguiding into the inappropriate branch. Additionally fin size needs to be smaller than maximum width and length so that it can rotate slightly in the Y-branch and go into the appropriate destination branch.

can come into contact with the branch point. The minimum width and length of the fin is related with this range. The minimum fin size is shown as Fig. 5b, which is similar to maximum fin size except that θ_f is related with L_T and w_R. Thus eqn (1) can be equally applied in calculating the minimum fin width.

Using these approximations, the range of fin length can be theoretically achieved with the following fixed values: w_R (62 μm) θ_T (45°), and θ_B (10°). The range of maximum and minimum width of the fin is plotted in eqn (1), (2) and (3) as shown Fig. 6. Area (b) indicates the range of fin size for stable sorting, which is the necessary fin size in this area to theoretically guarantee the sucess of sorting without error. Fins in area (a) are considered oversized because they cannot rotate at the Y-branch area. In area (c), particles are unstably sorted because fins can slide into the inappropriate branch.

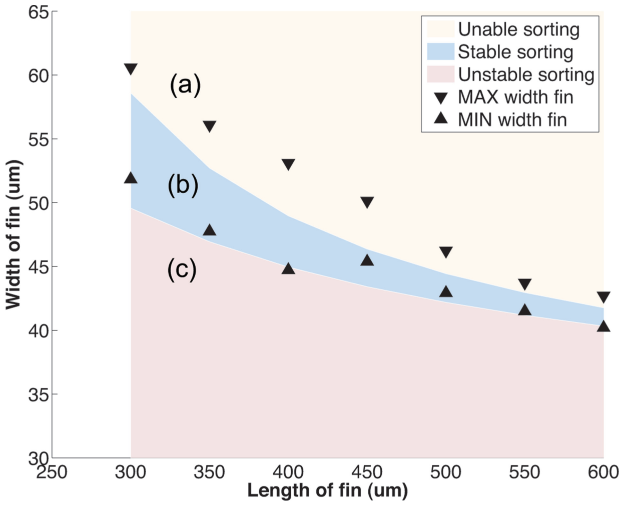

Fig. 6 The width range of fins that can be successfully sorted according to various fin lengths. Area (b) indicates size of fin for stable sorting. Upper boundary and lower boundary are obtained from eqn (1). Area (a) indicates the fin size, which could potentially fail to sort properly, area (c) is the clogging area, where the fin cannot rotate and sort because the fin is too long. ▼ is the maximum width of fin that can be sorted without clogging. ▲ is the minimum width of fin that can be obtained experimentally. θ_T: 45°, θ_B: 10°, w_R: 62 μm.

The maximum and minimum fin widths were obtained experimentally using the above conditions. For this experiment, fin lengths and width were configured by fabricating fins using Optofluidic Maskless Lithography (OFML).[17] The maximum and minimum widths obtained by the experiment are shown Fig. 6. The inverted triangle dots are plotted slightly above the boundary between unstable and stable and indicate maximum fin width that can be sorted without clogging. To prevent microstructures from bending at the Y branch (which would result in less predictable behavior), we used rigid particles fabricated by exposing a high UV light dose and applied not more than 10 psi in order to move the microstructures. Non-inverted triangle dots distributed on the graph (Fig 6) indicate minimum fin width that can be sorted successfully without error. We observed that within the range between maximum and minimum fin widths, the microstructures could be sorted without errors due to the lack of influence by hydrodamic factors. As the fin length becomes too long or too wide, the likelihood of successful sorting is decreased in line with theoretical predictions based on the channel geometry.

Since our approach uses a simple mechanical sliding mechanism we expect that it can be widely used as a sorting method over microscale distances, in which a wedge shaped microstructure can be fabricated on a grooved microchannel. This sorting technique uses fluid flow as the driving force so the particle movement at the Y-branch can be easily predicted since fluid flow has laminar characteristics at the microscale. However, the particle's movement at the nanoscale might be more complex than the movement at the microscale due to stochastic processes such as Brownian motion.

Experimental

Microfluidic device

PDMS-based microfluidic devices were fabricated using a soft-lithography replica molding process. We used photolithography for fabricating SU-8 (Microchem Corp., Newton, MA) mold onto a silicon wafer. Two layers of SU-8 mold were fabricated

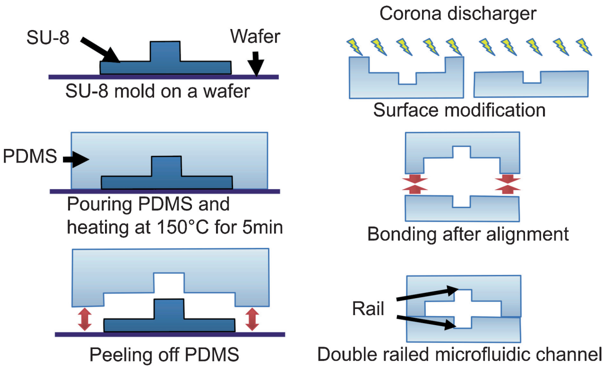

Fig. 7 The fabrication process for fabricating a double-railed microfluidic channel, bonding two PDMS microfluidic channels.

using a double coating and exposure steps with a single developing step. PDMS (Sylgard 184, Dow Corning) was poured on the mold and baked at 150 °C for 15 minutes before it was peeled off the mold. The height of the microchannel and the rail was 40 µm and 60 µm respectively.

In the fabrication process for making a double-railed microfluidic channel, a soft-lithography replica molding process was used for PDMS substrates. Next, the two PDMS microfluidic chips were bonded using a micro-aligner after surface treatment by a corona discharger. After bonding, the microfluidic device was heated on a hotplate in order to increase the bonding strength (Fig. 7).

Finned microstructure

Poly(ethylene glycol) diacrylate (PEG-DA, Sigma-Aldrich, M_n = 258) and photoinitiator (2,2-dimethoxy-2-phenylacetophenone) were mixed and used as a prepolymer. The prepolymer was introduced into the microfluidic channel which included a groove pattern. Patterned ultraviolet (UV) light was generated by an Optofluidic Maskless Lithography (OFML) system.[17] Since the groove works as a mold, polymeric finned microstructures were directly fabricated on the groove by *in-situ* polymerization. In order to produce a large number of microstructures for the experiment, we applied stop flow lithography for high-throughput fabrication of microstructure. A solenoid valve (LHDA0531515H, THE LEE) was used for composing a stop-flow lithography system. The height of the microfluidic channel and an oxygen inhibition layer determine the height of the fin and the body of the finned microstructure.

Sorting microstructures

Fluidic flow was controlled by syringe pump (Harvard Apparatus, model PhD2000). The range of the flow rate that we used for sorting ranged from 10–100 µl/min.

Conclusions

We have presented a method of sorting disoriented microstructures injected into a microfluidic channel according to rotation and flip. Fin structures were designed on the microstructure for controlling directional orientation using railed microfluidics. In order to sort microstructures by their head tail orientation we used a wedge shaped fin and Y-shaped railed microfluidic channel. Lean symmetric fins at the head and tail of the microstructures determined the sorting direction once the microstructures reached the branch point in a Y-shaped channel. For manipulating flipped and unflipped microstructures injected into the microfluidic channel, two grooves on the top and bottom of the channel were used. Taper-shaped entry guides directed microstructures into a double rail. The rail on the top (for flipped microstructures) and bottom of the channel (for unflipped microstructures), directed the microstructures down one of two channels at another branching point. Finally, we demonstrated simple fluidic assembly of prefabricated micro-latches, integrating these two sorting methods. Our present sorting method is completely autonomous, enabling high throughput sorting of microstructures in a solution based on their orientational status. Our work represents a first step in enabling fluidic assembly of highly heterogeneous microstructures for various applications including biochips and semiconductor packaging.

Acknowledgements

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