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Magnetically actuated microrotors with individual pumping speed and direction control

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We demonstrate an experimental realization of a microscale pump self-assembled from superparamagnetic colloidal spheres and driven by an external magnetic field, where a system of microelectrodes controls the pump rotor by dielectrophoretic force. Whereas an external magnetic field is used to assemble and drive the rotor, which allows parallel fabrication and actuation of many such devices, the microelectrodes enable control of an individual rotor and thus regulate pumping speed and direction of any single pump in the microfluidic device. Dielectrophoretically controlled micropumps can be fabricated with existing microfabrication techniques and can be easily integrated into complex microfluidic devices. © *2009 American Institute of Physics*.
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A major challenge in the field of microfluidics is the transport of fluids through the microscale channels in microfluidic devices,[1] where the fluid flows are usually driven and controlled by external pressure pumps and accompanying hardware connected to the devices by silicone tubing.[2] Such arrangements are somewhat impractical because of their size and limited portability, which contradicts the main idea of the laboratory-on-a-chip system, a device that should be simple, robust, compact and portable, allowing its use outside a stationary laboratory as well. External pumps also have a limited precision, whereas for bioassay and analysis methods precise fluid delivery is often required.

A more practical approach to pumping fluid flows is to eliminate the need for external pumping equipment by constructing microscale pumps within actual microfluidic devices. Several experimental demonstrations of such pumps have been reported where different strategies were used, from the use of deformable elastomer elements[3] to constructing micro-scale peristaltic pumps and rotors assembled from colloidal particles and driven by optical tweezers[1] or magnetic fields.[4,5] In the demonstration by Bleil *et al.*,[4] superparamagnetic colloidal spheres in a plane geometry self-assembled into rotating clusters under the influence of an external homogeneous in-plane rotating magnetic field. Such rotors with size of the order of a few micrometers were used to pump fluids through a test microfluidic circuit. The direction of the external magnetic field rotation determined the pumping direction while the magnetic field density and rotation frequency regulated the pumping speed of these pumps.

An external magnetic field can be used to aid self-assembly and actuation of many such rotors simultaneously, which makes it possible to operate a large number of pumps concurrently and thus enables parallelization.[4] The main disadvantage of this approach, however, lies in its inability to control the operation of an individual pump in a multi-pump device, which means the pumping action can be started, stopped or reversed only in all the pumps simultaneously. To enable control of an individual rotor the use of laser tweezers was reported,[4] however, this option is less practical due to the complexity and size of optical tweezers[6] setups.

In this letter, we present a simpler strategy for local control of a single micropump in a multipump microfluidic device by using dielectrophoretic force produced with microelectrodes. The time-averaged dielectrophoretic force $\langle \mathbf{F}_{\mathrm{DEP}} \rangle$ acting on a spherical particle in a medium in alternating electric field of frequency ω is given[7] by

$$\langle \mathbf{F}_{\mathrm{DEP}}(\mathbf{r}_0, \omega) \rangle = 2\pi\varepsilon_1 R^3 \,\mathrm{Re}\left\{ \frac{\varepsilon_2(\omega) - \varepsilon_1(\omega)}{\varepsilon_2(\omega) + 2\varepsilon_1(\omega)} \right\} \nabla [\mathbf{E}^2_{\mathrm{rms}}(\mathbf{r}_0)]. \quad (1)$$

Here R denotes the particle radius, $\varepsilon_{1,2}(\omega) = \varepsilon_{1,2} - \mathrm{i}\sigma_{1,2}/\omega$ the complex dielectric permittivity of the medium and the particle, $\sigma_{1,2}$ their conductivity and $\mathbf{E}_{\mathrm{rms}}$ the root-mean-square of the electric field. The magnitude and direction of the dielectrophoretic force acting on the particle are tunable because they depend on the gradient and frequency of the electric field, as well as on the complex dielectric permittivity of the medium.

We made use of dielectrophoresis by equipping each pumping site in the microfluidic device with two pairs of electrodes connected to an ac voltage source with frequency 100 kHz. The electric field near the electrodes is highly inhomogeneous, which induces dielectrophoretic force on the rotor and allows controlling its position in the pump chamber. Fluid flow direction can be reversed by switching the pumping rotor position in the chamber. In addition, by varying the magnitude of the voltage applied to the electrodes and thus adjusting the electric torque on the rotor, the rotation speed and therefore the fluid flow velocity can be controlled as well.

The microelectrodes were patterned into a 250 nm layer of chromium, which was deposited on a standard 3×1 in.^{2} microscope slide. A thin film of negative photoresist (Microchem, SU-8 2025) was coated onto the slide and the electrodes microstructure was patterned using direct ultraviolet laser structuring technique,[8] as shown in Fig. 1(a). We used a diode laser (Omikron Laserage GmbH, Bluephoton LDM375.20.CWA.L) with wavelength $\lambda = 375$ nm and for beam steering a pair of acousto-optic deflectors (AA Opto

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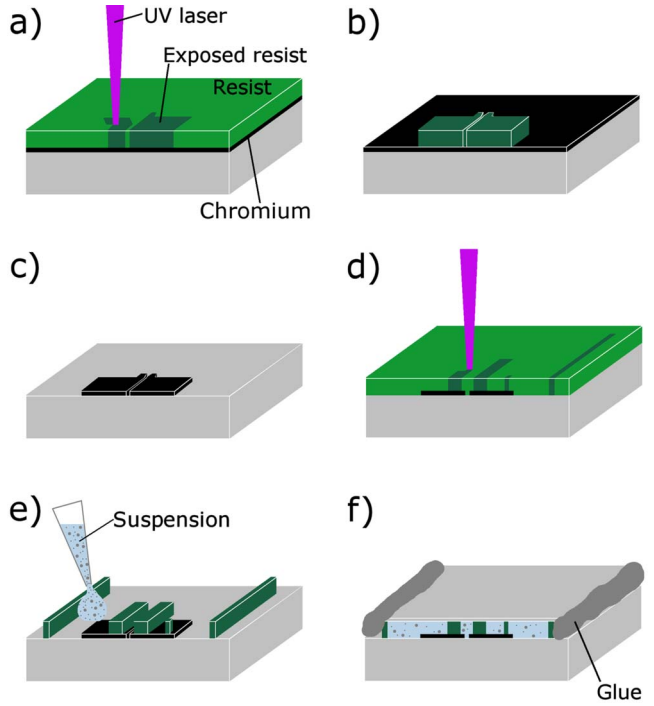

FIG. 1. (Color online) Schematic of microfluidic circuit fabrication. Layer thicknesses are not to scale. (a) Photoresist film on a chromium-coated (layer thickness 250 nm) glass substrate is illuminated with a UV laser beam. (b) Excess photoresist is etched to reveal the photoresist microstructure. (c) Excess chromium is etched and photoresist structure removed to obtain a chromium electrodes microstructure on glass. (d) The topological microchannel structure is patterned into a second layer of photoresist, in alignment with the chromium microstructure layer below. [(e) and (f)] The developed photoresist microchannel structure equipped with chromium electrodes is filled with colloidal suspension and sealed with a cover glass.

Electronic, DTSXY-400–405) and a beam steering controller (Aresis, BSC-160), which enabled a very precise laser intensity and beam positioning control on the photoresist film surface. This technique produces illumination patterns with the resolution better than 1 μm and does so in a faster and simpler way than the conventional photolithography method with the use of masks, because it omits the step of mask fabrication and the need for a direct contact with the photoresist surface during the illumination process. After developing the microelectrodes pattern, excess chromium not covered by the photoresist structure was etched and finally the remaining photoresist structure was removed, which revealed the chromium microstructure, as schematically shown in Figs. 1(b) and 1(c).

In the next step, another photoresist film with thickness of approximately 6 μm was coated onto the same glass slide and the topological structure of microchannels with 12 μm wide pumping sites was patterned. The microchannels had a square cross section with side of approximately 6 μm and were aligned with the chromium structure underneath, such that every pumping site was equipped with two pairs of electrodes, as shown in Fig. 1(d). The channels were filled with a suspension of superparamagnetic beads (diameter 4.4 μm, Dynal Biotech Dynabeads M-450), which were used to assemble the pump rotors, and smaller silica particles (diameter 2.3 μm, Bangs Laboratories), which were used as tracer particles to image the fluid flows. The microchannel structure was filled with the prepared suspension and sealed with a cover slip, as shown in Figs. 1(e) and 1(f). Figures 2(a) and 2(b) show the fabricated electrodes for one pumping site and a detail of the final two-layer structure. The method of using a photoresist layer to fabricate the microchannel structure was used for its simplicity; however, the more common soft-lithography technique[9] could have been used as well.

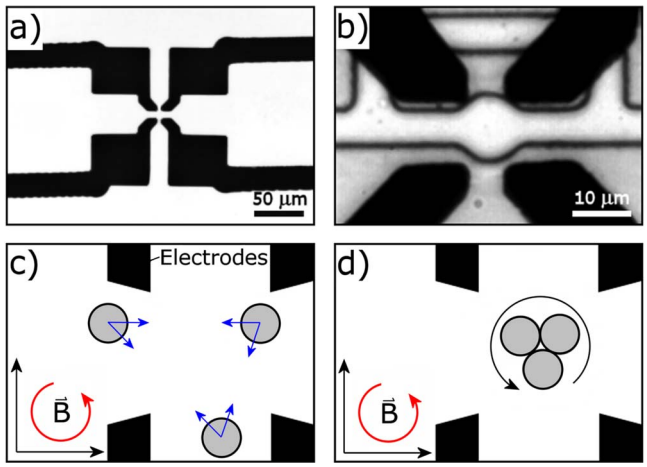

FIG. 2. (Color online) (a) Top view of a four-electrode microstructure in a 250 nm thick chromium layer on glass substrate. (b) Closeup view of a pumping site in a 6 μm wide and deep photoresist microchannel, equipped with four electrodes. (c) Schematic: superparamagnetic particles in a planar system assemble into rotating clusters in an external in-plane rotating magnetic field **B**. The magnetic field rotation and attractive forces between individual particles are schematically shown with arrows. (d) The cluster, rotating in the same direction as the external magnetic field, acts as a pumping rotor and can be controlled locally by the dielectrophoretic force due to highly inhomogeneous electric field near the electrodes.

The rotating magnetic fields needed to assemble and drive the pump rotors in the device were generated with two orthogonal coil pairs. Each coil was driven with an independent sinusoidal current source with incremental 90° phase shifts between adjacent coils to produce homogenous in-plane rotating magnetic fields. The magnetic field was rotated at frequencies up to 200 Hz and had a density of approximately 3 mT. Because the depth of the microchannels was comparable to the size of the superparamagnetic beads, the test microfluidic circuit could be regarded as a planar system. A magnetic field rotating in the circuit plane induced an isotropic attractive interaction between the superparamagnetic beads and caused them to self-assemble into a cluster. The cluster rotated in the direction of the field rotation and could be manipulated with dielectrophoretic force, as shown in Figs. 2(c) and 2(d).

When ac voltage is applied to the electrodes, the rotor becomes influenced by dielectrophoretic force, which points in the direction parallel to the electric field gradient and depends on the gradient magnitude and material properties as given by Eq. (1). In the example shown in Fig. 3(a), a rotor in the pump chamber is spinning counterclockwise, which for the given microchannel topology pumps the fluid flow in a particular direction, as indicated by the arrow. When the direction of the electric field gradient and thus of dielectrophoretic force is reversed, the rotor switches its position in the pump chamber, which also reverses the direction of the fluid flow without any change to the external magnetic field, as shown in Fig. 3(b). Note that since fluid flows in microfluidic channels are laminar and the Navier–Stokes equation solutions in this case are time reversible,[10] the pump symmetry must be broken to induce a net fluid flow,[11] which was in

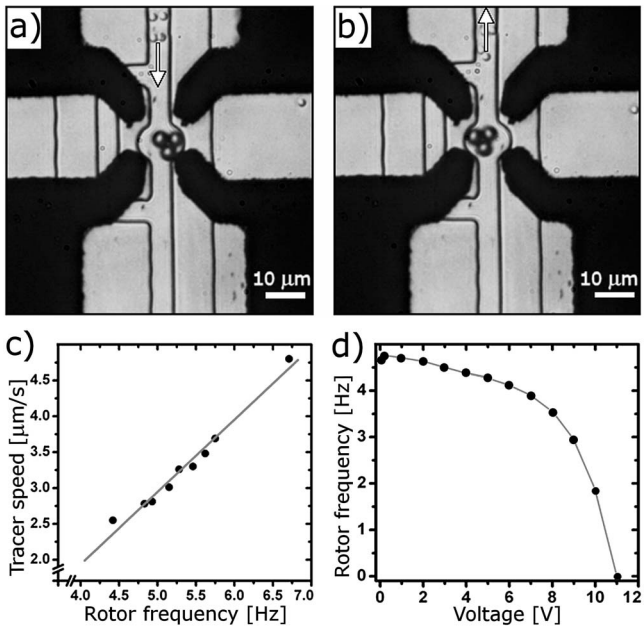

FIG. 3. (a) A rotor assembled from three superparamagnetic spheres (diameter 4.4 μm) rotates counterclockwise in an in-plane rotating external magnetic field. The rotating motion propels a fluid flow and causes movement of smaller silica tracer particles in the direction indicated by the arrow. (b) Reversing the direction of the electric field gradient due to the electrodes causes the rotor to switch its position in the pump chamber, which reverses the fluid flow without any change to the external magnetic field. By adjusting the magnitude of the voltage, the fluid flow speed can be regulated as well. (c) Speed of tracer particles as a function of frequency of rotation of the rotor. (d) Rotor rotation frequency as a function of voltage applied to the electrodes.

our case achieved with asymmetric position of the rotor in the pump chamber.

We characterized the constructed micropump by measuring its pumping velocity as a function of rotor frequency. The dependence, shown in Fig. 3(c), is linear; maximum speeds of around 5 μm/s at around 7 Hz were achieved. We also measured the pump rotation frequency as a function of applied voltage at the electrodes, shown in Fig. 3(d). The rotation frequency falls with increasing voltage and the increasing electric torque ultimately stops the rotor. It follows from the results that the rotor frequency and thus the pumping speed can be regulated by changing the magnitude of the voltage applied to the electrodes, without the need to change the frequency of the external magnetic field.

To conclude, we demonstrated a microscale pump useful for transporting fluids through channels in microfluidic devices, where the need for external vacuum pump systems to control fluid flows is eliminated. The pump rotor is assembled from superparamagnetic colloidal particles, where a rotating external magnetic field is used both to drive the rotor and to provide its structural integrity. A system of microelectrodes at the pump site is used to manipulate the rotor and hence control the direction and regulate the speed of fluid flow through an individual pump. In the case where a large number of such pumps, driven by the same external magnetic field, is present in a microfluidic device, it is of crucial importance to have an ability to address each individual pump and thus keep precise control over each component or part of the circuit system. The method presented here enables this control and can be integrated into complex microfluidic devices using existing microfabrication techniques.

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