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Patterned magnetic traps for magnetophoretic assembly and actuation of microrotor pumps

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We demonstrate a microscopic magnetic rotor pump for fluidic channels whose components are assembled in situ and powered by weak external magnetic fields (<150 Oe). A platform of patterned Permalloy microdisks and microcavities provided for the transport, trapping, and rotation of the superparamagnetic spherical microrotors. Parallel actuation of several rotors without direct physical link to external energy sources, tunable rotation speeds, and reversible drive torques offers significant advantages over macroscopic techniques to control flow within microfluidic devices. The effectiveness of trapping and transporting magnetic nanoparticles by the disks illustrate scalability to smaller, submicrometer sized devices. © 2011 American Institute of Physics. [doi:10.1063/1.3562037]

Microfluidic devices for diverse biological and chemical applications have shown superior performance over their macroscopic counterparts. However, their widespread adoption requires fluid handling devices that can be integrated into microchannels to achieve not only separation, mixing, and dilution of chemical reagents but to also offer portability, biocompatibility, low cost, and precision. Several micropump techniques relying on, for example, deformable membranes, electroosmosis, and clusters of magnetic spheres have been utilized and actuated by optical tweezers or magnetic fields. Often, the assembly of these clusters depends on the number and locations of microspheres in the channel which may be difficult to control magnetically and require a separate manipulation technique such as electrophoresis or optical tweezers. In this regard techniques utilizing thin patterned magnetic films have proven useful for micron-resolution trapping and manipulation of such magnetic particles. Here we present a magnetic colloidal micropump which uses mobile traps on patterned films that are remotely maneuvered by weak external magnetic fields to assemble the desired number of microrotors in situ and to actuate them.

The experimental layout is illustrated in Fig. 1. Circular Permalloy (Py, Ni0.8Fe0.2) disks (10 μm diameter and 60 nm thick) and cavities of the same dimensions in a Py film are lithographically patterned on a silicon surface [Fig. 1(a)]. Photoresist (Rohm and Haas, SPR-200-7.0) was utilized to fabricate a 15 μm wide channel with 9 μm tall conduit walls [Fig. 1(b)] that is capped from above [Fig. 1(c)] with a 5 mm thick rectangular sheet of poly(dimethylsiloxane) (PDMS). The cavities that hold the microrotors are positioned asymmetrically in the channel and lie close to one of the sidewalls to pump fluid. Inlet and outlet ports entrenched in the PDMS provide access to the microchannel. Five 5 cm diameter electromagnet coils [Fig. 1(d)] yield programmable applied magnetic fields (Hx, Hy, and Hz) up to 150 Oe in three orthogonal directions and generate tunable magnetic forces and torques.

The microrotors, which are 8.5 μm diameter superparamagnetic spheres (Spherotech CM-80), are introduced in aqueous solution through the PDMS inlet port. As discussed below, application of sequential magnetic fields provide trapping, transport and loading of the miniature rotors into the 10 μm cavities where they are subsequently driven by the external fields. The tracking of 2.1 μm diameter nonmagnetic tracer particles (Spherotech CP-20) by LABVIEW routines enables the fluid flow velocities within the channel to be determined as a function of the frequency of the in-plane rotating magnetic field and the number of microrotors.

FIG. 1. (Color online) [(a)–(c)] Sample fabrication steps (features not to scale). (a) Permalloy disks and cavities are patterned on silicon surface. (b) Walls of microchannel are patterned from SPR-220 photoresist. (c) PDMS sealed to the photoresist contains fluid from above, and ports act as fluid reservoirs. (d) Magnetic fields are applied to micropump using five electromagnets while observations are made with optical microscope. (e) Real image of micropump with Py disks, cavities, and channel walls along with coordinate axes.
The energy landscapes of the traps are illustrated in Figs. 2(a)–2(f), showing the field dependence of the energy profiles for the superparamagnetic spheres. The insets in Figs. 2(a)–2(f) illustrate corresponding real images of a trapped rotor. Similarly, the maximum in U (repulsive site) always occurs outside the cavity or within the boundary of the disk [Figs. 2(b), 2(c), and 2(f)]. Thus, in the presence of H_x, the microsphere is trapped away from the edge of the disk while reversing H_y leads to its relocation to the opposite side of an adjacent disk [Figs. 2(b) and 2(e)]. As a result, the microsphere can be transported between neighboring disks in an array by suitably changing the orientation of the applied fields H_x, H_y, and H_z. The same approach however does not allow for transport between cavities. In this case switching the direction of H_y relocates the attractive trap to the opposite side within the same cavity. Hence, as the microspheres are transported across an array of disks, spheres (i.e., rotors) that have been previously loaded within a cavity (see below) remain trapped in the same cavity.

The microspheres are introduced into the channel through the PDMS inlet port and are transported between disks toward a cavity by a sequence of in-plane field rotations and reversals of H_x. A sphere is introduced into the desired cavity by taking advantage of its interaction with the channel wall through directed movement to the wall, and rolling the microsphere along the wall into the selected cavity by synchronized in-plane fields. Once individual microspheres are introduced into the required number of cavities, remaining spheres are magnetically transported away from the channel, leaving only the cavity-trapped spheres that then function as the field-activated microrotors. This in situ rotor assembly that utilizes the same external tuning fields to load the microspheres and also drive the pump hence overcomes the need to integrate separate approaches (such as optical tweezers or electrodes) to functionalize the pump. The magnetic disks are also effective for manipulation of submicron-sized (~500 nm) particles [Fig. 2(g)], thus illustrating the present micropump design can be readily scaled down to the nanoregime. The potential to miniaturize to even smaller dimensions is evidenced in the report of similar manipulation of magnetic micellular constructs that are only ~50 nm in size.

Once in place, the cavity-held microspheres spin in-step with the externally driven rotating H_x, H_y, and H_z fields as the H_z field is kept constant. The magnetic and drag forces, together with limits set by the electronics allow for the maximum tracer velocity to occur at a field frequency of ~20 Hz. As shown in Figs. 3(a) and 3(b), for a given field rotation direction, placing the rotor closer to one sidewall will specify a flow direction. Thus, while each microrotor will rotate in the same direction as governed by the applied field, the relative positioning of the cavities within a network of channels will determine the pumping direction through each sector. The flow track can also be reversed by simply switching the direction of rotation of the fields. These features, pumping, tracking with tracer particles, and reversibility, are evident in...
the supplemental video\textsuperscript{16} for the case of three rotors driven by external fields.

The fluid velocity is measured as a function of field rotation frequency and number of microrotors [Figs. 3(c) and 3(d)] in a region where fluid flow is uniform, far from the cavity [Fig. 3(a)]. As expected, the pumping rate increases linearly with the rotational frequency until about 20 Hz, beyond which the microsphere is unable to fully synchronize with the rotating magnetic field. Further, Fig. 3(d) illustrates that at a given frequency of rotation (20 Hz), the tracer flow speed increases linearly from 2 \( \mu \text{m/s} \) with one rotor to about 13 \( \mu \text{m/s} \) with eight rotors in series. The pump efficiency can also be increased by use of magnetic particles that have a bigger net magnetic moment, which will allow for faster rotation for a given applied field.

To conclude, we have fabricated a magnetically actuated micropump where fluid is driven by a series of individual spheres that act as microrotors. Weak magnetic fields enable \textit{in situ} loading of the spheres into the microfluidic channel as well as actuation of the pump. The pumping speed is controlled by the rotation frequency of applied fields as well as the number of cavity-held microrotors. Patterned magnetic traps have been shown to be effective for manipulating nano-sized particles which suggests that this pump design could be scaled down to submicron sized length scales. This capability holds promise to not only increase the areal density of pumps but also to enhance the complexity of fluidic networks for specialized uses.

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\textsuperscript{16}See supplementary material at http://dx.doi.org/10.1063/1.3562037 for a video of pumping, tracer particle tracking, and flow reversibility driven by three rotors within a micropump.