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Manipulation of ferrofluid droplets using planar coils

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In this letter, the authors report a system for magnetic manipulation of ferrofluid droplets and their dynamic behavior. The magnetic field was generated by an array of planar coils, which were fabricated on a double-sided printed circuit board (PCB). The permanent magnetic moment of the ferrofluid droplet was created by the field of a pair of permanent magnets. The motion of the ferrofluid droplet is further aligned in a virtual channel formed by a pair of planar coils. Two other planar coils on the other side of the PCB drive the droplet along this virtual channel. The direction of the droplet motion can be controlled by reversing the electric current in the coils. Based on the experimental results, a larger droplet size, a lower viscosity of the surrounding medium, and a higher electric current will increase the droplet velocity. © *2006 American Institute of Physics.*
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The field of microfluidics recently witnessed a paradigm shift from the continuous-flow to the droplet-based concepts, where sample droplets can be stored and manipulated in an immiscible liquid. Droplet-based microfluidics has a huge potential for interesting applications such as chemical analysis and protein crystallization.[1] Due to the dominant role of surface-related phenomena, microdroplets can be manipulated by surface stresses.[2] In microfluidics, surface stresses are usually modified by electrostatic force such as electrowetting[3] and dielectrophoresis[4] or by its temperature dependence.[5] Magnetic force is another interesting option for the manipulation of microdroplets. Magnetic force is proportional to both magnetic moment and the gradient of the magnetic field. The magnetic moment is proportional to the volume, which may be a disadvantage in the microscale. However, due to the small size, a high magnetic field gradient can be achieved with microcoils. Magnetic force was used widely for handling magnetic beads in microfluidic devices.[6] Rida *et al.* used an array of planar microcoils to transport magnetic beads in a glass capillary.[7] Recently, the same research group utilized magnetic beads suspended in liquid droplets as actuators. The magnetic beads was able to induce magnetic forces, which are strong enough to complete tasks such as droplet transport and droplet splitting.[8]

The drawback of using magnetic beads is that they are too large with diameters ranging from 250 nm to 6 μm.[8] The magnetic force acting on each bead can redistribute the beads inside the droplet. The redistribution of magnetic beads in the droplets leads to the deformation of the droplet. In the worse case, a small droplet with magnetic beads may be separated from the original larger droplet. The original droplet without magnetic beads can no longer be manipulated. In this letter, we report the use of microcoils for manipulating ferrofluid droplets. The magnetic particles in a ferrofluid has a diameter on the order of a few nanometers. At this size, the random movement of the particles is larger than the magnetic force. Thus the dispersion of these particles is stable even under a strong magnetic field. Ferrofluids are paramagnetic and have very low hysteresis. All these

properties lead to the possible easy manipulation of a micro-ferrofluid droplet with planar microcoils. Pekas *et al.*[9] reported the detection of microferrofluid droplets formed in a microchannel using giant magnetoresistance sensors. Larger magnetic beads have been used widely in biochemical assays and showed their biocompatibility. Thus, a ferrofluid droplet can potentially be used as a reaction platform for handling samples in lab-on-a-chip applications.

We report here a system for manipulating ferrofluid droplets. Figure 1 shows the basic setup of this system. The main part of the setup is a double-sided printed circuit board (PCB). Two planar coils were etched on each side of the PCB. In Fig. 1, the black lines represent the coils on the front side of the PCB, while the grey lines represent the coils on the back side. Each coil has 13 windings. The coil wire has a cross section of 40×1000 μm^2. Two permanent magnets (NdFeB) were placed on a steel sheet, which carries the PCB device. The permanent magnets induce a large uniform magnetic field perpendicular to the motion direction x of the ferrofluid droplet, and consequently, polarizes the magnetic
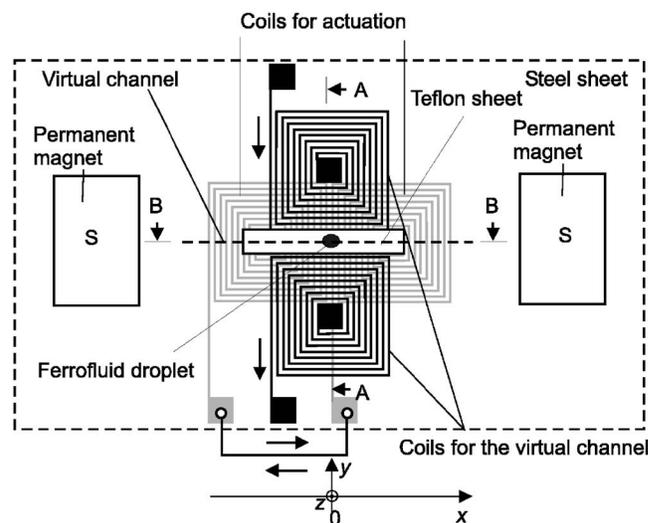

FIG. 1. Actuation concept for the manipulation of a ferrofluid droplet (schematic, not to scale). The grey coils are on the back side of the PCB, while the black coils are on the front side.
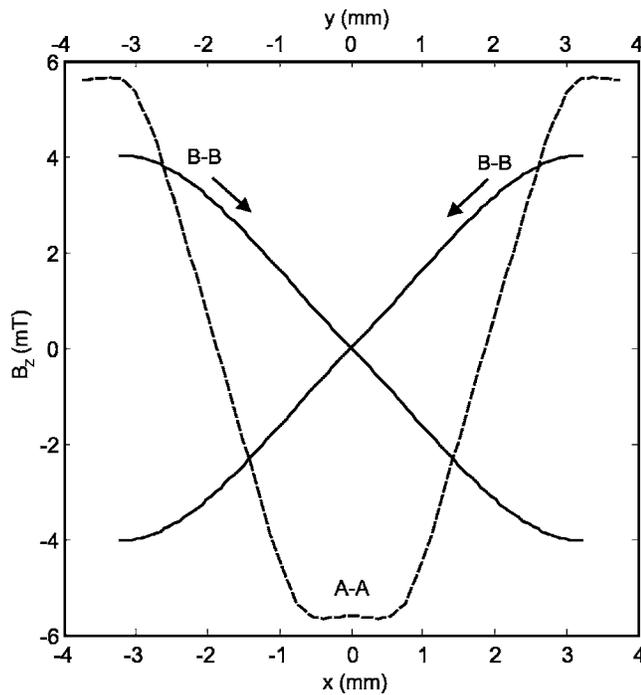
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FIG. 2. Simulated magnetic flux fields generated by the virtual-channel coils (A-A)and the driving coils (B-B).

FIG. 3. (Color online) Recorded image sequence from the experiment.

particles in the ferrofluid. Thus, the whole ferrofluid droplet can then act as a liquid magnet, because these magnetic particles are uniformly dispersed in the droplet. The fields generated by the two top coils (black in Fig. 1) are permanent and have the same sign. These fields form a potential valley between the coils, where the gradient in the y direction is zero (Fig. 2). Thus, these fields work as a "virtual channel" for the ferrofluid droplet. The ferrofluid droplet is confined in this virtual channel and can only move in the x direction. The two coils on the back of the PCB (gray lines in Fig. 1) are connected in series, so that their fields always have opposite signs. The field gradient between the two coils has the same sign, allowing the droplet to move in a prescribed direction. The motion direction can be changed if the current in the coils is reversed.

We first estimate the inductivity of the actuating coil to justify the use of a static magnetic field in an analytical description. The inductance of a planar spiral coil with a square shape can be estimated as[10]

$$L = \mu_r \mu_0 \frac{n^2 d_{avg} c_1}{2} \left(\ln\left(\frac{c_2}{\rho}\right) + c_3 \rho + c_4 \rho^2 \right), \qquad (1)$$

where μ_r, μ_0, and n are the relative permeability of the medium, the permeability of space, and the number of turns, respectively. With an inner width d_{in} and an outer width d_{out}, the two geometry parameters of the above equations are the average diameter $d_{avg}=0.5(d_{out}+d_{in})$ and the fill ratio $\rho =(d_{out}-d_{in})/(d_{out}+d_{in})$. The four constants for a square coil are given as $c_1=1.27$, $c_2=2.07$, $c_3=0.18$, and $c_4=0.13$.[10] With $d_{in}=1.5$ mm, $d_{out}=6$ mm, and $n=13$, the coil used in our experiments has an inductance of $L=8.45\times10^{-7}$ H. With a contact resistance of approximately $R=1$ Ω of the relay used in the switching circuitry, the response time of the current, and consequently, the magnetic field is $t=3\tau=3L/R \approx 2.54\times10^{-6}$ s. This response time is four or five orders of magnitude faster than the switching period of the driving
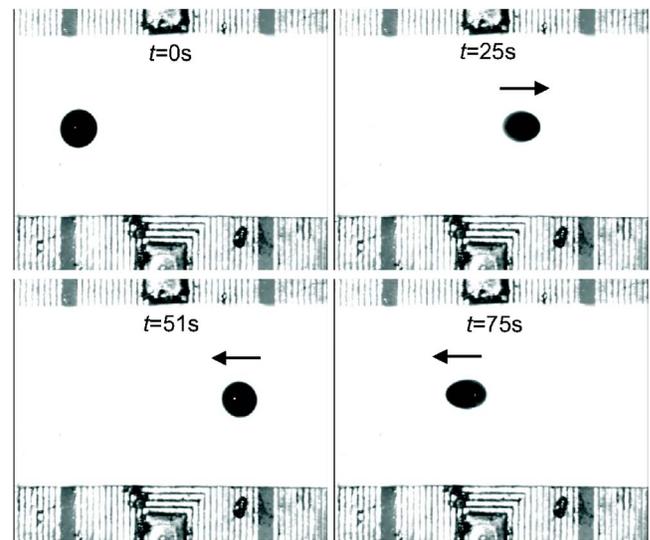
current. Thus, a static magnetic field can be assumed in the analytical description.

The static magnetic flux field $B_z(x)$ was numerically simulated with a finite element analysis package (ANSYS) using the given geometry and current density (Fig. 2). With this magnetic flux field, the force balance between the acceleration, the drag force, and the driven magnetic force can be described as a function of the droplet center position x.

The ferrofluid (APG S10n) used in our experiment was purchased from Ferrotec (http://www.ferrotec.com.). The carrier liquid is synthetic ester oil, which is immiscible to silicone oil. The viscosity, the density, and the surface tension of the ferrofluid at 25 °C are $\eta_{ff}=0.406$ kg/ms, $\rho_{ff}=1330$ kg/s, and $\sigma_{ff}=32\times10^{-3}$ N/m, respectively. The saturation magnetization and the initial susceptibility of this ferrofluid are 44 mT and $\chi=1.6$, respectively.[11] Silicone oils were purchased from Sigma Aldrich. We used two oils with different viscosities to investigate the effect of viscous friction ($[-Si(CH_3)_2O-]_n$, kinematic viscosity of $\nu=50$ cSt) and ($[-C_7H_8OSi-]$, kinematic viscosity of $\nu=100$ cSt). Both oils have approximately the same surface tension $\sigma=2.03\times10^{-7}$ N/m and density $\rho=960$ kg/m^3. In our experiments, the ferrofluid droplet was suspended in silicone oil, on top of a 0.5 mm thick Teflon sheet. The higher density of the ferrofluid ensures that the droplet remains at the bottom surface, while the high hydrophobicity of the Teflon surface allows the droplet to keep its spherical shape. The two virtual-channel coils were supplied with a constant current of 750 mA. The direction of the current in the driving coils was switched every 50 s using a control circuit. The periodic motion of the ferrofluid droplet was captured with a charge-coupled device camera. The camera was synchronized with the switching signal to record the droplet position at a given time instance. Figure 3 shows an example of the recorded image sequence from this experiment. It is apparent that the droplet is stretched and deformed during the passage.

The center point position of the droplet was evaluated using the recorded images. Results of the droplet position as a function of time are depicted in Fig. 4. The motions of ferrofluid droplets with different sizes under the same conditions are shown in Fig. 4(a). Since the driving magnetic force is a body force, a larger droplet will have a better volume to
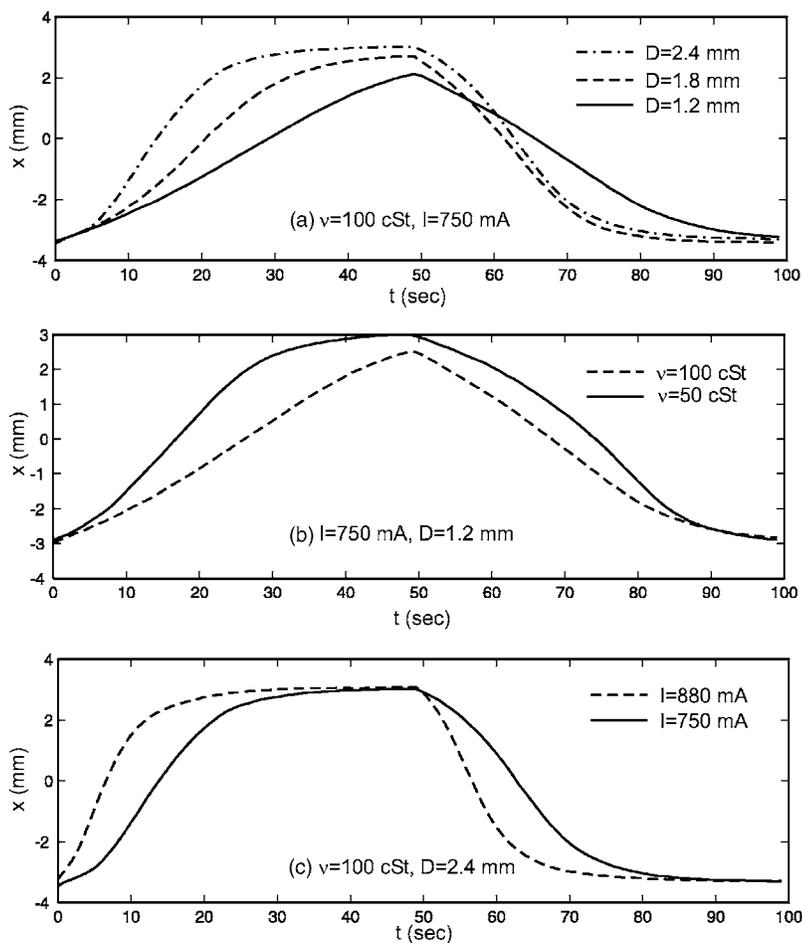
FIG. 4. Measured droplet positions vs time with (a) different droplet sizes (750 mA driving current, in 100 cSt silicone oil), (b) different viscosity of the carrier medium (750 mA driving current, droplet diameter of 1.2 mm), and (c) different driving currents (droplet diameter of 2.4 mm, in 100 cSt silicone oil).

surface ratio or a larger ratio between the magnetic force and the drag force. A larger droplet can accelerate faster and reach the final position in a shorter time. Figure 4(b) shows the effect of drag force caused by the viscosity of the surrounding medium. With the same driving condition and droplet size, a less viscous medium leads to a faster droplet velocity. Figure 4 shows the impact of the driving current on the droplet motion. For the same center-to-center distance between the coils, a larger driving current means a larger magnetic flux gradient. Thus, a larger driving current also leads to a higher droplet velocity.

We have demonstrated a simple concept for manipulating ferrofluid droplets using planar coils. The coil was fabricated on a double-sided PCB. The ferrofluid droplet was polarized by a uniform magnetic field imposed by a pair of permanent magnets. Two coils with the same current directions form a potential well to trap the droplet in a virtual channel. Two other coils with opposite current directions drive the droplet with its flux gradient. The direction of the droplet motion is controlled by switching the current direction in these driving coils. Since the concept is based on a body force, a large droplet will have a better ratio between the driving force and the drag force and can move faster. The drag force is determined by the droplet size and the surrounding medium. The driving force for the droplet can be controlled by the current passing through the coils. This actuation concept can be used for transport and sorting applications in droplet-based microfluidics. The results show the

potential use of ferrofluid droplets as both a vehicle and a microreaction platform for droplet-based lab-on-a-chip applications.

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