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Design of high-magnetic field gradient sources for controlling magnetically induced flow of ferrofluids in microfluidic systems

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Abstract

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Keywords

Microelectronics Research Center, Microanalytical Instrumentation Center, Ferrofluids, Microfluidics, Microscale flows, Flow control, Finite element methods

Disciplines

Electromagnetics and Photonics | Electronic Devices and Semiconductor Manufacturing | Engineering Physics | Fluid Dynamics

Comments

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The use of miniature electromagnets for ferrofluid-actuated liquid dispensing into microfluidic channels has been investigated by numerical simulations using the finite element method and measurements of fluid displacement and flow rate. The simulations illustrate the effect of structural and geometrical parameters of single and paired solenoid coils on the magnetic force experienced by the ferrofluid. Dual solenoids were used for extended fluid displacement. Ferrofluid positioning and flow rates were controlled also by using a solenoid with an iron core. The experimental measurements of fluid flow in capillaries were used to validate the modeling calculations. The results can be used as a basis for the development of on-chip ferrofluid-based devices integrated with microfluidic architectures. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1557361]

I. INTRODUCTION

Ferrofluids are magnetizable colloidal suspensions of fine (e.g., 3–15 nm) ferrimagnetic particles in a liquid.[1–3] In a magnetic field gradient, the magnetized particles in the ferrofluid are driven in the direction of the field gradient, and simultaneously drawing along the liquid carrier.[1–3] This allows precise positioning and displacement of the ferrofluid using magnetic field gradients, and enables their use in a range of applications such as sealing, damping, heat transfer, and liquid delivery systems.[2,4,5]

Parallel with the expanding utility of ferrofluids, there is a growing need for small-size instrumentation in environmental monitoring, chemical synthesis, and the delivery of drugs.[6,7] Such small-size, microfluidic-based instruments use minute amounts of material, and can reduce analysis/synthesis times and generated waste. While significant advances have been realized,[6,8] the construction of small-size pumps and injectors and their integration with microfluidic channels remain a significant challenge.[9]

Recently, the utilization of a ferrofluid as the actuation element in a micropipette and in a small-size pump was explored using microelectromagnetic (MEMag) devices. In these devices, a magnetic field gradient, generated by toroids[10] or permanent magnets,[11] was utilized to draw, dispense, and pump liquids in direct or indirect contact with the ferrofluid. Optimization of MEMag generators through the process of trial and error is time consuming and costly. Therefore, numerical simulations were used to evaluate the use of MEMag generators with various structural and geometrical parameters.

We employed the finite element method (FEM) to obtain the generated magnetic field, magnetic field gradient, and magnetic force. The nonlinear $B-H$ curve of the ferrofluid plug was incorporated into the FEM calculations. These results were used to design an optimized MEMag generator configuration for controlling the ferrofluid position, flow rate, and the extent of fluid displacement.

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II. FEM NUMERICAL SIMULATIONS

As a magnetic field source, a solenoid was chosen because the magnitude of the magnetic field and magnetic field gradient can be varied by changing solenoid parameters such as the radius (R), length (L), and number of turns (N). The Maxwell equations can be solved by the finite element method and they can then be used to determine movement of a ferrofluid plug by the magnetic force generated by the solenoid. We first calculated the magnetic energy $W(s,i)$ of the plug for displacement s and current i given by

$$W(s,i)=\int_V \vec{M}\cdot\vec{B}\,dV, \tag{1}$$

where $\vec{M}$ is the magnetization, $\vec{B}$ is the magnetic flux density, and V is the volume of the ferrofluid plug. Next, the magnetic force was obtained by differentiating Eq. (1) with respect to the variable s as

$$F=-\left.\frac{dW(s,i)}{ds}\right|_{i=\mathrm{const}}. \tag{2}$$

The nonlinear $B-H$ curve of the ferrofluid was incorporated into the FEM calculations used to optimize the design of the electromagnets. The magnetic field strength and field gradient generated by a solenoid with and without an iron core were evaluated to control the movement and positioning of a ferrofluid plug. The effect of the core dimensions (i.e., its length and thickness) was also evaluated using the FEM simulations.

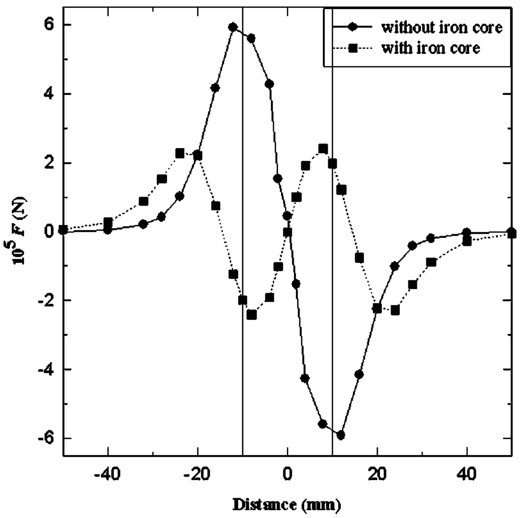

FIG. 1. Magnetic force at the center of a 15 mm ferrofluid plug along the central axis of a solenoid with or without an iron core. The center of the solenoid is at $x=0$. The solenoid parameters are length $L=20$ mm, radius $R=14$ mm, and number of turns $N=100$; the current $i=1$ A and the thickness t of the core $=2$ mm.

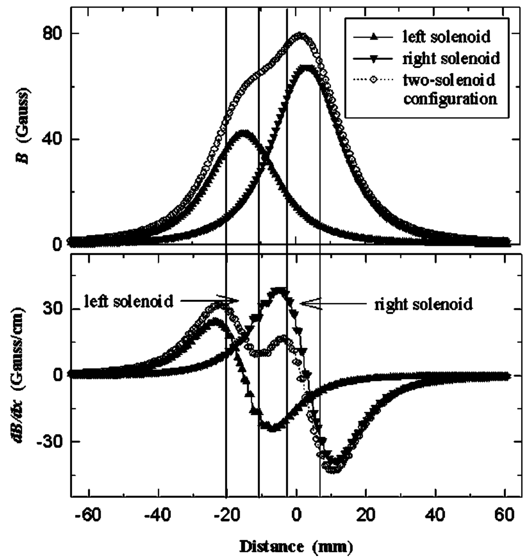

FIG. 2. Magnetic field strength and field gradient generated by two solenoids with different numbers of turns along a common central axis (left solenoid: solenoid radius $R=14$ mm, current $i=1$ A, number of turns $N=100$, and solenoid length $L=10$ mm; right solenoid: $R=14$ mm, $i=1$ A, $N=160$, and $L=10$ mm. The distance between the centers of the two solenoids is 18.3 mm).

III. EXPERIMENT

Experiments were performed to test the feasibility of using solenoid coils as magnetic field generators for magnetically induced flow of a ferrofluid plug. The ferrofluids used in the experiment were EMG 900 (initial saturation magnetization 900 G) and EMG 901 (initial saturation magnetization 600 G),[4] which are dispersions of iron oxide particles in a light mineral oil. A ferrofluid plug was placed in a capillary at different positions along the central axis of the solenoid. The solenoids were wrapped directly around the capillary, or over a spacer, to increase the solenoid radius. The spacers were made of glass, a nonmagnetic plastic material, or iron. One- and two-solenoid configurations, based on the optimized configurations obtained from the finite element numerical simulations, were evaluated.

IV. RESULTS AND DISCUSSION

The FEM simulations showed that in the region outside the solenoid coil, further away from its edge, the solenoid with the larger radius generates a higher field strength and field gradient. The simulations also showed that, as the length of a solenoid increases, the field strength increases more gradually from the region outside the edges towards the center of solenoid. Therefore, a solenoid with larger radius or length was preferred to enable liquid displacement over an extended distance as long as the solenoid was able to generate a sufficiently high field gradient to initiate movement of a ferrofluid placed in the region outside the solenoid.

The simulation results for a solenoid with an iron core showed that, along the central axis, the field strength increased from the region outside the solenoid to a maximal value near the edge of the solenoid. The field then decreased from the edge towards the center of the solenoid. This was due to the high permeability of the soft iron core, which resulted in an increase in the flux lines passing through the core area. Figure 1 shows the calculated magnetic force experienced by a plug of ferrofluid moving along the center axis of the solenoid with or without an iron core. As seen in Fig. 1, in the absence of an iron core, the force dropped to zero at the center of the solenoid, while in the presence of an iron core, the force dropped to zero near the edge of the solenoid, although it extended more gradually over a larger distance from the solenoid edge.

To further extend the range of the force acting on the ferrofluid, we used a design of two solenoids in series. Figure 2 shows the field strength and field gradient generated by a pair of solenoid coils placed along the same central axis. For comparison, we also plot the field strength and gradient generated by each solenoid separately. The two solenoids had similar dimensions but different numbers of turns. As can be seen, the field gradient extended over a larger distance for the solenoid pair than for the individual solenoids. This is due to the higher maximal field strength at the center of the solenoid that has a larger number of turns compared with the solenoid, which has a smaller number of turns. A similar effect can be obtained by using two solenoids with different radii or different lengths. This configuration can be extended through the use of several coils with increasing number of turns, or a single coil with a gradually increasing density of turns along its length.

Experiments showed that the ferrofluid movement stopped inside the solenoid in the absence of an iron core, whereas in the presence of an iron core, the ferrofluid stopped before reaching the edge of the solenoid, as expected from the calculations. Figure 3 shows the average volume flow rate (F_v) of a ferrofluid plug as a function of the initial distance between the centers of the plug and the solenoid for different currents. In the absence of an iron core, the force changes sharply near the edge of the solenoid, as shown in

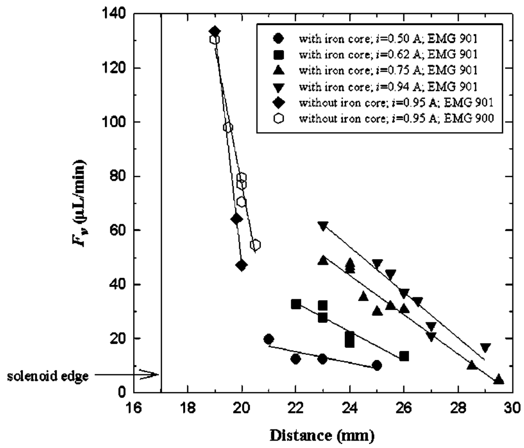

FIG. 3. Average flow rate at different currents as a function of the distance between the center of a ferrofluid plug and of a 17 mm long solenoid with 80 turns. The radius of the flow channel is 0.5 mm, the radius of the solenoid is 6.25 mm, and the thickness of the iron core is 2 mm. The ferrofluid was diluted with toluene at a weight ratio of 1:1.

Fig. 1. This resulted in sharp changes in F_v near the edge of the coil, as seen in Fig. 3. In contrast, the changes in the force and consequently in F_v were more gradual in the presence of the ferromagnetic core. Hence a ferromagnetic core was advantageous for producing smaller F_v values and smaller changes in F_v during flow.

Using a configuration of two solenoids with differing numbers of turns as a field generator (see Fig. 2) resulted in a ferrofluid displacement ~2.5 times larger than that observed using the single solenoid with the larger number of turns. As mentioned, a single coil with a gradually increasing linear density of turns is expected to similarly drive flow over an extended distance. This was demonstrated by examining the flow of a plug of hexane separated from the ferrofluid plug by an air gap. The gradually structured coils were wrapped around capillaries (0.25–1 mm radii) that contained the ferrofluid. The hexane plug was positioned in microfluidic channels (65–375 μm radii) connected to the ferrofluid-containing capillary. Hexane displacements exceeding 5 cm were observed in the microfluidic channels. The average volume flow rate ranged from 0.8 to 500 μl/min for currents ranging from 0.1 to 0.9 A. Approaches to further decrease the flow rate, needed for analytical applications, and maintain a constant flow rate are currently under investigation.

In summary, FEM simulations enabled the evaluation and design of electromagnets for enhanced performance of ferrofluid-based, magnetically actuated microelectromagnetic devices for dispensing liquid into microfluidic reservoirs and channels. Control of ferrofluid displacement and flow rate was achieved through evaluation of the effect of the geometrical parameters of solenoids, with and without an iron core, based on FEM numerical simulations. These results will serve as a basis for the development of on-chip ferrofluid-based devices integrated with microfluidic architectures.

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