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Microelectromagnetic ferrofluid-based actuator

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Computer simulations were used to investigate the performance of a microscale ferrofluid-based magnetic actuator developed for liquid dispensing in microfluidic channels. The actuation was based on the movement of a ferrofluid plug in a magnetic field gradient generated by on-chip effectively infinite parallel conductors. The movement, positioning, and retaining of ferrofluid plugs with different lengths at various locations along a microfluidic channel were investigated for two cases. In case (a), the magnetic field gradient was generated by a single conductor; when the ferrofluid reached its equilibrium position, the current was switched off and the nearest neighbor conductor was energized. A similar, consecutive on/off current switching was performed for case (b), where a set of conductors was energized simultaneously.
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I. INTRODUCTION

Magnetic field gradient is widely used for magnetic trapping, transport, and filtration/separation of magnetic particles.[1–3] Magnetic field gradient can also be used to manipulate a ferrofluid, which is a stable suspension of fine (~10 nm diameter), single-domain, ferrimagnetic particles in an aqueous or organic carrier. As a result, ferrofluids can be used in a wide range of applications[4–6] by exploiting both their magnetic and liquid properties.

This work describes a microelectromagnetic (MEMag) device in which the movement of a ferrofluid plug is actuated by consecutive switching of on-chip current-carrying conductors. The movement of the ferrofluid plug can be used to dispense a liquid that is in direct or indirect contact with the ferrofluid. Hence, this device is being developed for delivery of microliter and nanoliter amounts of fluids in microfluidic channels for biological and chemical applications. The ability to use on-chip conductors to drive the ferrofluid plug results in devices that are more flexible in design and, consequently, more versatile in function in comparison with devices based on moving permanent magnets.[6]

II. DESCRIPTION OF THE PROBLEM

The device consisted of on-chip, parallel, effectively infinite conductors. In case (a), a single conductor is energized, while several parallel conductors are energized simultaneously in case (b). The width of each conductor was 100 μm and the height was 1 μm. The distance between the centers of two adjacent conductors was 200 μm. These dimensions allowed us to simplify the problem to a two-dimensional case as shown in Fig. 1 for case (b).

Calculations were performed assuming Al conductors, which can handle a maximal current density of 10^{-3} A/μm^2, limiting the maximal operational current to 100 mA. The ferrofluid plug was placed in a long capillary (100×100 μm^2 cross section) that was situated 100 μm above the MEMag device, parallel to its plane and perpendicular to the direction of the current flow (see Fig. 1). In all calculations, a ferrofluid with EMG 900 (Ferrotec) properties was considered. This ferrofluid exhibits a superparamagnetic behavior with a saturation magnetization of 72 kA/m.

Using finite element method, the Maxwell equations were solved numerically for the entire system. In order to calculate the magnetic force acting on a ferrofluid plug, the energy, E, of the plug in the external magnetic field was calculated as a function of the distance, x, between the centers of the current-carrying conductor and the plug

$$E(x) = -\int_V \boldsymbol{M}\cdot\boldsymbol{B}\,dV, \tag{1}$$

where $\boldsymbol{B}$ is magnetic flux density, $\boldsymbol{M}$ is magnetization, and V is the volume of the plug. The capillary parallel component of the magnetic force, $F(x)$, acting on a plug is the derivative of the energy (1)

$$F(x) = \frac{dE(x)}{dx}. \tag{2}$$

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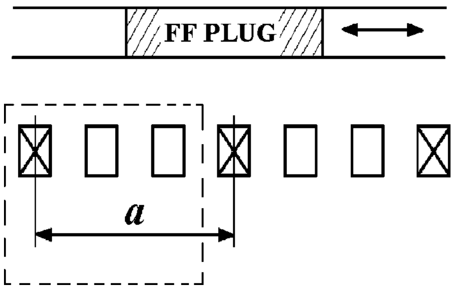

FIG. 1. Schematic view of the device design geometry for case (b). The conductors are perpendicular to the shown plane. The energized conductors, separated by a distance *a*, are presented by crossed rectangles. The arrows indicate possible directions for ferrofluid (FF) plug movement.

Equation (2) was used to compute $F(x)$ for different lengths, L of the ferrofluid plug.

As mentioned, the movement of the plug was investigated for two different cases: (a) consecutively inserting the next neighbor conductor and simultaneously shutting down the previously energized conductor, and (b) consecutively inserting every *n*th conductor ($n>2$ and constant) and simultaneously shutting down the previously energized neighboring conductors (see Fig. 1 for $n=3$). The insertion and shutdown were carried out when the plug reached its equilibrium position, i.e., the total magnetic force was zero.

III. RESULTS AND DISCUSSION

The magnetic force as a function of x for case (a) is shown in Fig. 2 for ferrofluid plugs with different lengths. It was found that the magnetic force has a symmetry $F(-x) = -F(x)$, enabling plug movement in opposite directions: positive $F(x)$ values cause plug movement towards the energized conductor, which is left to right in the Fig. 2. Negative $F(x)$ values (not shown) represent movement in the opposite direction. It can also be seen that $F(x)$ has a maximum, F_{MAX}, and for $L \geqslant 300$ μm (this limit depends on the dimensions of the plug and conductor), the position of F_{MAX}, is at $x=-L/2$. At this position, the entire plug is placed as close as possible to the conductor (i.e., one of the edges of the plug is exactly at $x=0$) and all parts of the plug are subjected to the positive force. For $L \leqslant 300$ μm (not shown), the position of the maximum is near 100 μm. F_{MAX} initially increases linearly with increasing length (i.e., volume) of the ferrofluid plug. However, as L further increases, the increase in F_{MAX} becomes more gradual until a saturation value is reached (see Fig. 3). This behavior is due to a decrease in the magnetic force acting on parts of the plug that are more distant from the energized conductor (i.e., where the magnetization approaches zero). For case (a), a

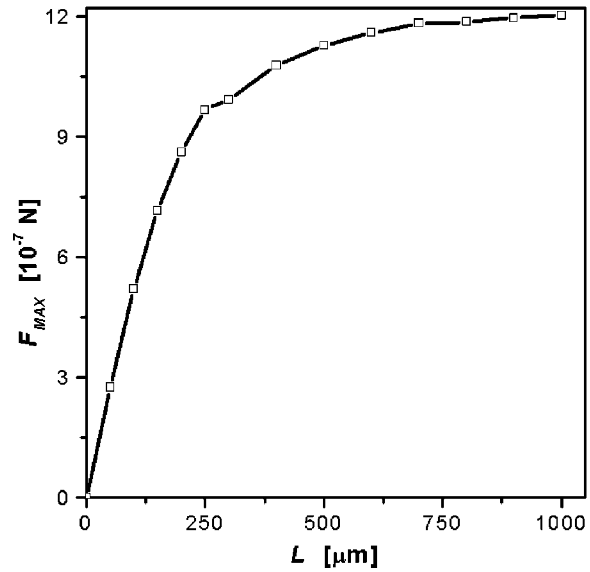

FIG. 3. The dependence of the maximal value of the magnetic force F_{MAX} on the length L of a ferrofluid plug for case (a). The applied current is 10 mA.

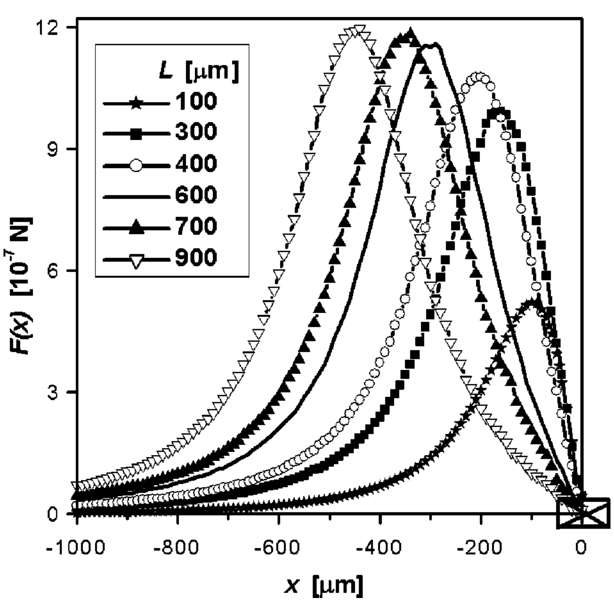

FIG. 2. The magnetic force $F(x)$ as a function of the distance x for different ferrofluid plug lengths for case (a). An energized conductor is presented as the crossed rectangle. The applied current is 10 mA.

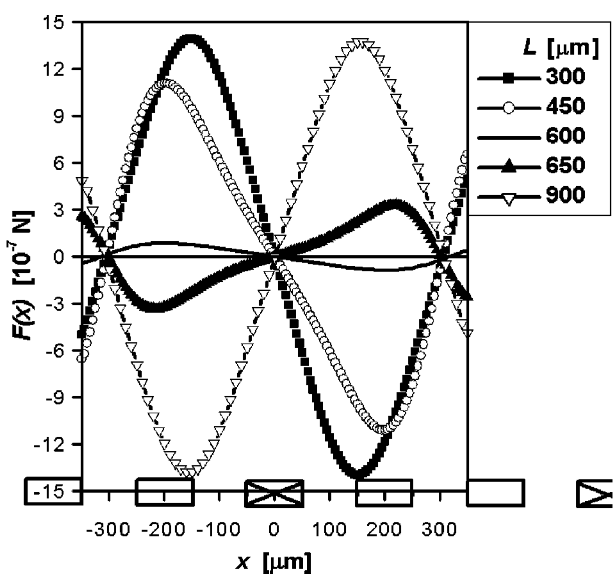

FIG. 4. The magnetic force $F(x)$ as a function of the distance x for different lengths of ferrofluid plugs for case (b). Energized conductors are shown as crossed rectangles. The applied current is 10 mA.

plug with any length can be moved and its equilibrium position is reached when the center of the plug is located just above of the center of current-carrying conductor.

The magnetic force as a function of x for case (b) is depicted for different values of L in Fig. 4, where a value of $n=3$ was chosen as an example. It was observed that $F(x)$ in this case possesses a spatial periodicity in x with a period of $a=200n$ μm and, at a first approximation, the periodicity in $F(x)$ with respect to L is $2a$. Therefore, only plugs with length $0 \leqslant L \leqslant 2a$ will be examined herein. As for case (a), positive and negative values of $F(x)$ cause plug movement in opposite directions. Note, that for case (b) there are many positions where the magnetic force is equal to zero (see Fig. 4). These positions are at $x=ka/2$, where k is an integer. However, only half of these positions are stable and this half is different for different L values.

When $0 \leqslant L \leqslant a$ the movement of the plug closely parallels case (a): its equilibrium (and stable) position is reached when the center of the plug is just above the center of one of the current-carrying conductors, i.e., k is even. However, for a plug with $a \leqslant L \leqslant 2a$ the equilibrium position is reached when the plug center is exactly in the middle between two nearest current-carrying conductors, i.e., k is odd.

For case (b), plugs with a length close to $L=ma$, where m is an integer (see Fig. 4 for $m=1$; i.e., $L=600$ μm), will not move, independent of the magnitude of the current; that is, $F(x)$ is zero at any position.

It is worth noting that for plugs with length $a/2$ or $3a/2$, the maximum magnetic force for case (b) is *larger* than for case (a) (compare $F(x)$ values for 300 and 900 μm plugs in Figs. 2 and 4). This difference is caused by the presence of several energized conductors, which affect the magnetic flux density and the gradient.

It was found also that for both cases (a) and (b) the magnetic force shows a square-law increase with increasing current. This behavior reflects the relatively low current (up to 100 mA) used to energize the MEMag device. In such cases, the magnetic field is proportional to the current and the magnetization of the ferrofluid is a linear function of magnetic field, far from the saturation region. Increasing the current further (e.g., by using gold, rather than aluminum, conductors that can handle a significantly higher current density, i.e., up to 1 A/μm^2), will increase the magnetic force but disturb the square-law increase, leading to a more linear behavior. However, one should be aware of the possibility of breakage of the ferrofluid plug into smaller parts for case (b) due to adjacent conductors that exert force in opposite directions; this situation can potentially disjoint or rupture the plug.

In summary, two cases for an on-chip microelectromagnetic device were evaluated, where a ferrofluid plug is used as an actuator for delivery of microliter or nanoliter amounts of fluids. The device properties were studied numerically using finite element analysis. It was shown that the movement of a ferrofluid plug in a microfluidic channel could be controlled utilizing different designs of microelectromagnets and different plug lengths. Additionally, depending on the design parameters, ferrofluid plugs can serve as on-chip valves. The utility of on-chip designs for ferrofluid-actuated devices for chemical and biological applications is currently under investigation.

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