MICROFLUIDIC PUMP BASED ON ARRAYS OF ROTATING MAGNETIC MICROSPHERES

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ABSTRACT

We demonstrate a novel, flexible and biocompatible method to pump liquid through microchannels without the use of an external pump. The pumping principle is based on the rotation of superparamagnetic microspheres around permalloy disks, driven by an external in-plane rotating magnetic field. By placing the permalloy disks close to the edge of the channel, a net flow of 9 μm/s was generated in the middle of the channel. This pumping principle is especially suited for flow controlled medium recirculation in culture chambers, opening ways towards portable, on-chip closed cell culturing [1].

KEYWORDS
Magnetic microspheres, pumping, permalloy, closed microsystem, rotating.

INTRODUCTION

The manipulation of magnetic microspheres using permalloy patterns and external fields has been demonstrated by Gunnarsson et al [2]. In this work we use this movement to generate a net flow using an external rotating in-plane magnetic field. Using this field the magnetic elements of the array are magnetized, causing a force on the magnetic microspheres. This in turn causes the magnetic microspheres to rotate around the soft magnetic disks. In a closed-loop structure the rotating microspheres will cause a net fluid flow, as shown in Figure 1.

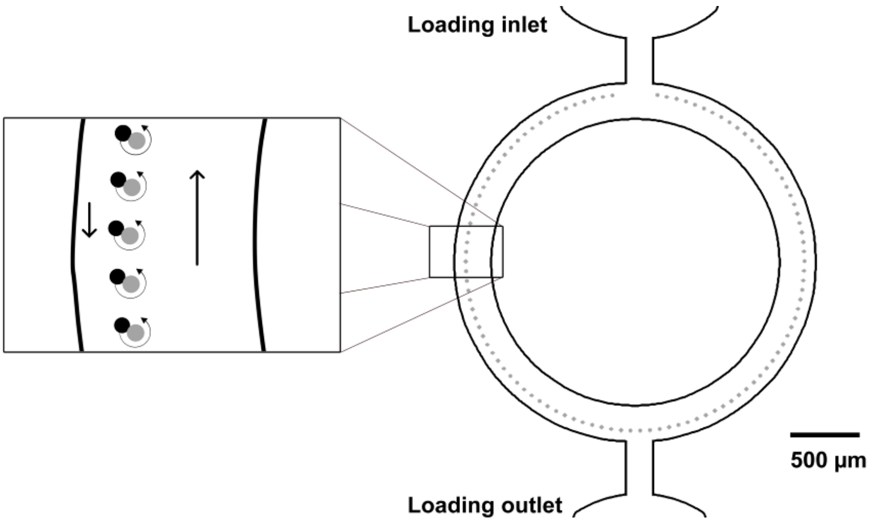

Figure 1. The closed pumping channel with permalloy disks (gray) and magnetic microspheres (black). The arrows indicate the direction of flow. Since the disks are placed closed to the edge of the channel, the net flow is upwards.

For optimal pumping, the magnetic microspheres should be as large as possible, as long as they fit in the channel. Larger microspheres not only experience more force in the magnetic field generated by the disks, but also displace more liquid per cycle. Apart from the pumping motion, also effective mixing is obtained by the stirring action of the microspheres.

The fluidic pumping operation is based on the asymmetry in the liquid displacement during the forward and backward movement of magnetic microspheres rotating around soft magnetic disks located outside the center of a (micro-)channel as shown in Figure 2. Assuming 3D Stokes flow and neglecting no-slip conditions at the wall, one can estimate the pumping efficiency by integrating the flow profile over the channel boundaries. These calculations show that the pumping efficiency is strongly dependent on the gap between the rotating microsphere and the wall, with the highest efficiency being achieved by minimizing this gap. Due to their position near the edge of the channel, the drag caused by the channel wall will cause an asymmetry in liquid displacement, resulting in the net pumping motion. The effect is multiplied by using an array of magnetic disks along the channel wall (see Figure 1). The rotational frequency of the external magnetic field controls the movement of the magnetic microspheres and therefore the generated net fluid flow.

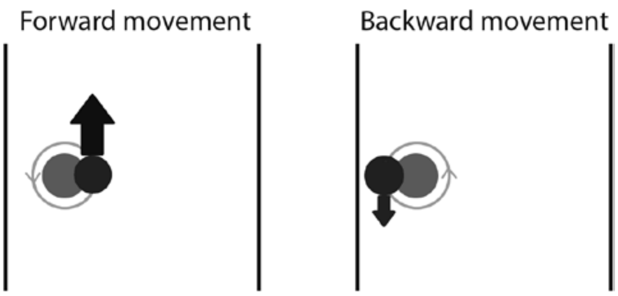

Figure 2. When a magnetic bead located close to the wall in a microfluidic channel rotates around a magnetic disk, the asymmetry in liquid displacement of the forward and backward movement results in a net pumping movement.

This principle enables the use of an externally programmable flow in a closed microfluidic system. A major advantage of such a magnetic actuation principle is, that it reduces the size of the microfluidic control drastically, because for pumping no tubing and no syringe pump will be required. Therefore the total setup can be reduced to the chip in a chip holder and a magnetic control device for the actuation. Hence a small portable and programmable pumping system with a relatively inexpensive actuation setup in principle would be obtained. Usual problems with an external pump connected to a chip by tubing, such as air bubbles and dead volume introduced by these components, would be circumvented by using a closed fluidic pump on chip.

MANUFACTURING

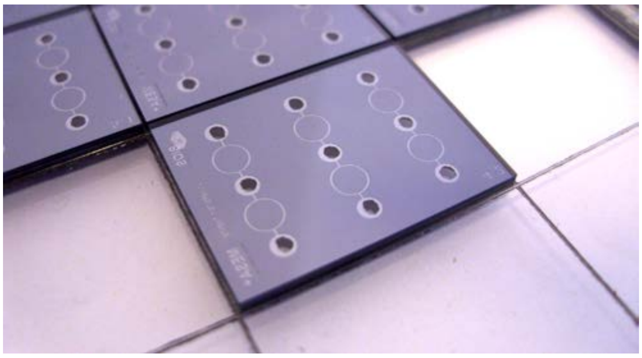

Figure 3. A picture of the fabricated chip, with a size of 2.0cm x 1.5cm.

To fabricate the magnetic structures, a 480 nm permalloy film was sputtered on a silicon wafer and patterned using conventional lithography and etching, yielding an array of disks with a diameter of 25 µm. The adhesion of the permalloy film to silicon and glass substrate was poor, therefore a chromium adhesion layer was applied. The 37 µm deep microchannels were wet etched in a borofloat glass wafer. To get tightly sealed channels, both wafers are bonded anodically at 425 ^{o}C. A picture of the resulting chip is shown in Figure 3.

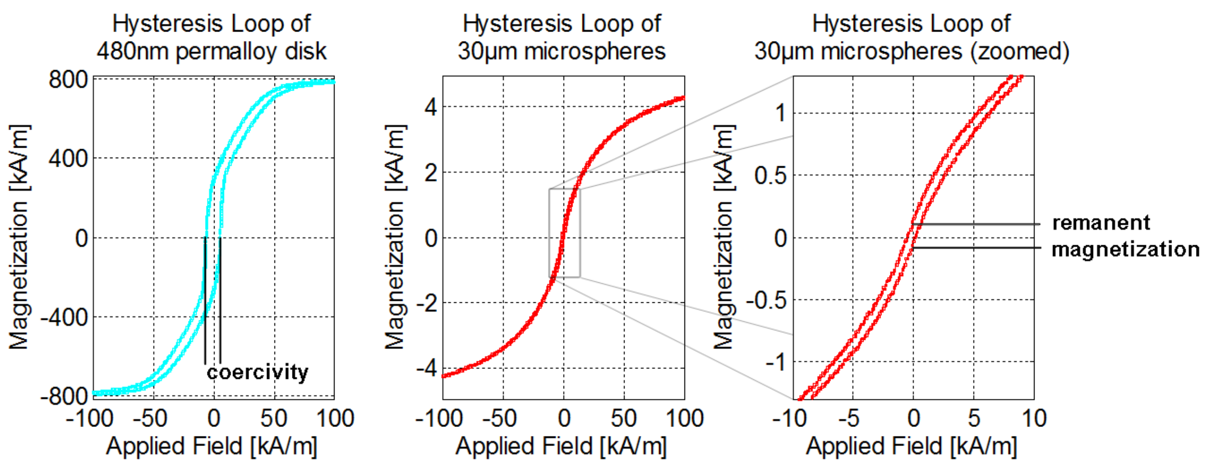

Figure 4. The magnetization curves of the permalloy disks (left) and the superparamagnetic microspheres (middle and right). The remanent magnetization of the magnetic microspheres is small.

A disadvantage of this heating step is that it increases the coercivity of the permalloy (Figure 4). However the hysteresis loop of the permalloy film after heating (Figure 4, left), shows that the increase in coercivity is limited to 6 kA/m. It was possible to saturate the fabricated magnetic disks by using a relatively small magnetic field of approximately 65 kA/m. This magnetic field strength could be reached easily with conventional electromagnets.

EXPERIMENTAL

Pumping experiments were performed using bio-compatible, 30 µm superparamagnetic microspheres [3]. The maximum achievable rotation frequency depends on the magnetic force between the disk and the magnetic microsphere. To maximize this force, the magnetization of the microspheres should be as high as possible. Their hysteresis loop (Figure 4, right) shows that the remanent magnetization of the microspheres is quite small, which will prevent permanent sticking of the particles to the disk or to each other. The external magnetic field was generated by a magnetic quadrupole electromagnet, with a field of 95 kA/m at rotating frequencies of up to 10 Hz. Red polystyrene microspheres of 3 µm [4] were added to visualize the flow in a microscope. Only partial coverage of the disk array by rotating beads was obtained mainly due to sticking problems.

RESULTS

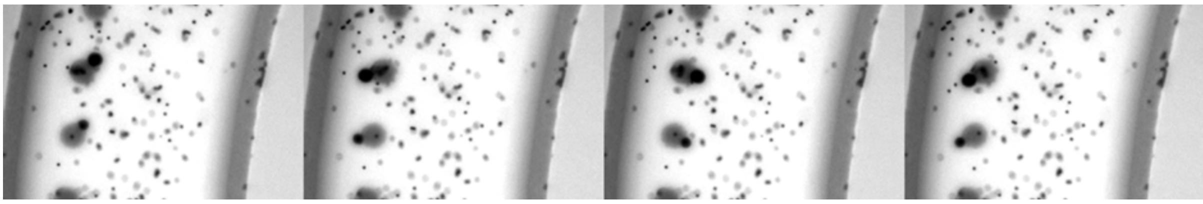

Figure 5. Images of moving particles in the channel. The dark magnetic microspheres are rotating around the gray permalloy disks. The small dark dots are the polymer indicator microspheres.

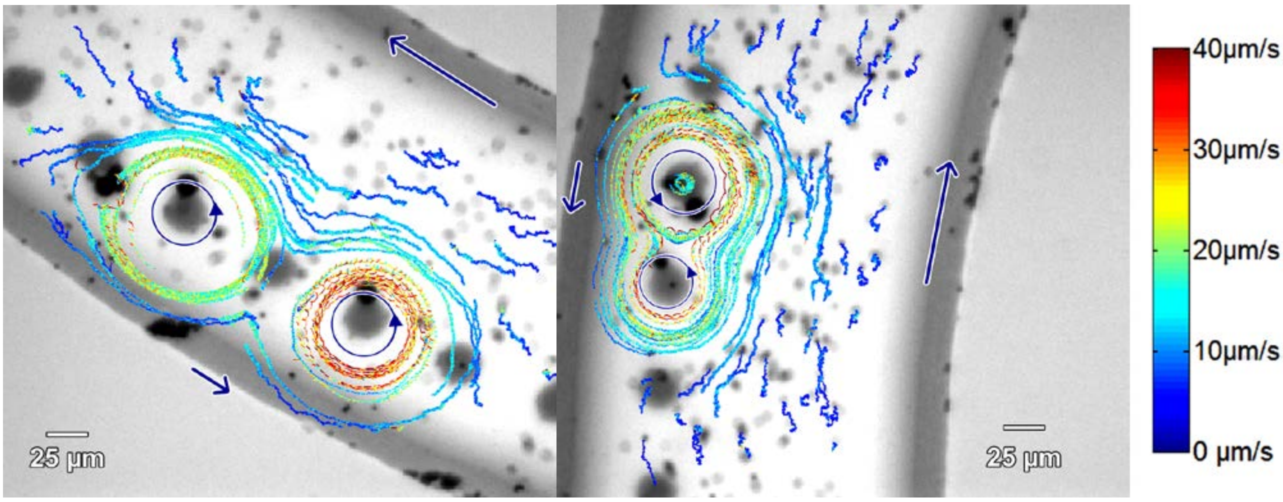

Figure 6. The observed movement of the indicator microspheres at a magnetic field frequency of 5 Hz, indicating a net liquid flow in the channels. The maximum velocity of 40 µm/s is limited by the particle tracking algorithm.

The rotation frequency of the microspheres could be controlled well up to 6 Hz, resulting in a maximum microsphere velocity of 470 µm/s. Images of these moving microspheres are shown in Figure 5. Above this frequency the microspheres did not perform exclusively a circular motion, but also started to spin around their own axis or stopped moving completely. The highest pumping rate was obtained at the maximum rotation frequency, where the microsphere movement was still purely circular. Even though coverage of the disks by microspheres was only partial in our setup, the pumping principle did work well. Figure 6 shows an analysis of the recorded paths of the indicator microspheres. Two rotating beads spaced one disk are shown on the left and two rotating beads without spacing are shown on the right of Figure 6. There is a net flow in the middle of the channel with an average velocity of 9 µm/s.

We expect that further optimization of the geometry and microsphere coverage can lead to a significant increase of the flow rate. The magnetization of the microspheres could also be increased. Proper coating would make the microspheres biocompatible and could also prevent sticking.

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