Gentle Micropump based on Microelectromagnetic Actuator

A. T. Al-Halhouli*, A. Waldschik* M. I. Kilani** and S. Büttgenbach*

*Technische Universität Braunschweig, Institute for Microtechnology, IMT
Alte Salzdahlumer 203, 38124 Braunschweig, Germany, a.al-halhouli@tu-bs.de
**College of Engineering, King Faisal University, Al-Ahsa, 31982 Saudi Arabia
**Mechatronics Engineering Department, University of Jordan, Amman 11942, Jordan

ABSTRACT

This work introduces the concept of a new electromagnetic micropump that depends on rotating two hard polymer magnets in an annular channel through simultaneous energization of a set of microfabricated copper coils. The magnetic field in microcoils is controlled to move one magnet while the other is attracted between the inlet and the outlet ports. At the end of each pumping cycle, magnets change their function between holding and moving. The fabrication process of pump components, circular actuator, polymer magnets, and glass cover, will also be presented. In addition, preliminary experiments done on a circular actuator to rotate one magnet will be described. Results showed that a maximum rotational speed up to 600 rpm can be obtained in a fluidic channel of 380 µm height and 1500 µm width. Further visualization experiments showed that the electromagnetic force between the magnets and coils needs more investigations in order to achieve pumping action.

Keywords: micropumps, electromagnetic, actuator, bio-medical.

1 INTRODUCTION

Microfluidics is an interesting field of research that is developing rapidly, and appears to have promising applications in chemistry, biology, and medicine. It offers attractive advantages for human beings such as: portability, low cost, minimized sample volume, fast detection, decreased analysis time, compactness, etc [1].

Recently several microfluidic control devices, microfluidic measurement devices, and microfluidic testing devices attracted interest in various applications (i.e., biomedical microdevices, and fuel cells) [2]. Among these devices are pumps, valves, bioreactors and mixers [3-6].

Micropumps represent the heart of microfluidic systems and their development has been governed by the physics of microfluidics, which is characterized by several physical phenomena (e.g., large surface area to volume ratio, viscous forces dominating over inertia and laminar flows) [7].

Since the beginning of research on micropumps, a variety of mechanical and nonmechanical micropumps have been investigated [8-10]. Such pumps have not generally met the demands imposed by biomedical systems, and have not been a part of commercial biomedical systems.

Due to its attractive characteristics, high field energy density and fast response time, and due to the availability of new technologies for fabricating magnetic microcoils and polymer magnets, electromagnetic actuators have been incorporated in novel pump designs [2,3, 11]

Recently, meso-scale pumps based on electromagnetic force have introduced a gentle pumping method at relatively low shear stresses [3, 12]. The pump offers attractive advantages such as capability of handling a wide range of fluids, can be operated at low shear stresses and bubble tolerant. These advantages allow the proposed micropump to be successfully implemented in the highly demanding biological and biomedical microsystems.

In this work, the new electromagnetic pumping concept based on microfabricated actuator using polymer magnets will be introduced. The actuator fabrication process and preliminary tests will be presented.

2 PUMPING CONCEPT

The proposed micropump is comprised of an electromagnetic circular microactuator, two polymer permanent magnets and a flat cover that includes the inlet and outlet ports (Fig. 1).

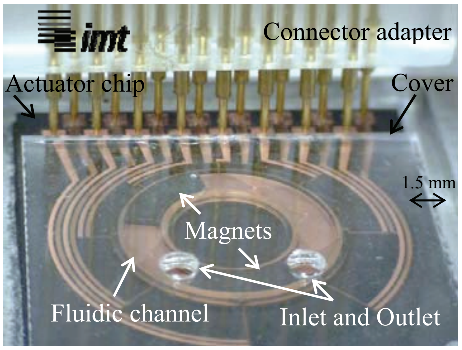

Fig. 1: Photograph of the micropump components

The new electromagnetic pumping concept depends on controlling the rotation of two polymer magnets placed in a circular fluidic channel in same polarity under the influence of a moving electromagnetic field (Fig. 2). Coils located between the inlet and outlet attract one magnet and are called holding coils, while the rest apply a moving magnetic force on the free magnet to achieve pumping action.

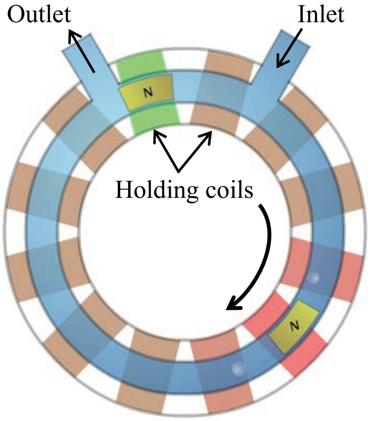

Fig. 2: Schematic of the pumping concept

For the microfabricated pump, the energization scheme is controlled through the actuator chip in a set of electroplated copper coils (eight coils, C1-C8) arranged below the fluidic channel (Fig. 3). One or two of the Coils (C8 and C1) are holding coils between the inlet and outlet ports, so they attract one magnet fixed between the inlet and outlet ports which will act as a valve and separates the inlet flow from the pumped one and forced the flow out of the channel, while the others (C2-C7) are used to create a rotating magnetic field on the free magnet to create pumping action on the fluid. Due to magnet movement, the fluid is pushed out through the outlet and withdrawn into the channel from the inlet.

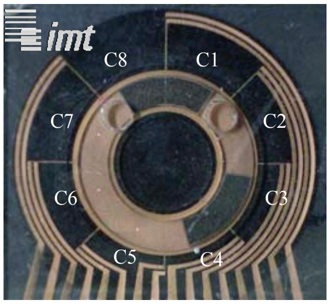

Fig. 3: Actuator energization scheme.

As the free magnet is reaching the outlet and while one coil is separating between the magnets, they begin to exchange their roles and move together, where the holding one is accelerated and attracted along the channel to act as a moving piston while the moving one is decelerated until it stops between the inlet and outlet ports and acts as a valve. This exchange in roles continues and a pumping action is obtained.

This concept was successfully tested in a meso-scale model [3] at different rotational speeds. However, it is still under investigation for the microscale pump, where the magnetic force needs to be optimized.

3 MICROFABRICATION PROCESS

The main three micropump components, actuator chip, permanent magnets and cover, are fabricated separately using UV-lithography. In the following subsections, the microfabrication process will be described.

3.1 Circular Actuator Chip

The microactuator chip is processed on a ceramic substrate where planar two-layer copper micro-coils are electroplated on SU-8 mask followed by patterning of SU-8 microchannels directly over the microcoils.

The fabrication process sequence starts with the lower conductors of the double layer coil. A mold of AZ9260 is patterned and filled with a 15 µm thick copper layer by electroplating. After stripping the AZ9260 mold, a 20 µm SU-8 insulation layer is spun onto the electroplated coils. This layer provides openings for through connections to the upper coil layer. Both connections and upper conductors are likewise structured by AZ9260 molding and copper electroplating. After that, a second SU-8 isolation layer spun onto again. A sample of fabricated coils of 15 µm copper segment width and 37 turns is shown in Fig. 4.

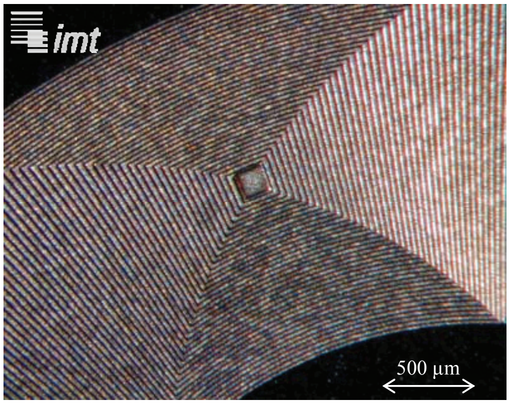

Fig.4: microfabricated double layer spiral coils.

Finally, SU-8 is spun onto the coils for structuring the microfluidic channels. The channel with the cover comprises the pump chamber. Different channel widths of 250 – 1500 µm and heights of 200 – 800 µm are patterned.

3.2 Polymer Permanent Magnets

Polymer magnets fabrication offers flexibility on patterning different magnet shapes and dimensions according to the design requirements. Their fabrication process begins by electroplating a sacrificial copper layer onto a glass substrate followed by a thin patterned SU-8 base plate layer. After that, a 200 - 800 µm high SU-8 layer is spun onto the base layer and structured to provide the filling form for the polymer magnet. The magnetic powder (MQP-S-11-9) [13] is embedded in a polymer matrix, inserted into the mold and baked out. After baking, a polishing process follows to level the compound structure and to remove waste residues. Patterned structures are released from substrate by etching the copper sacrificial layer (Fig.5).

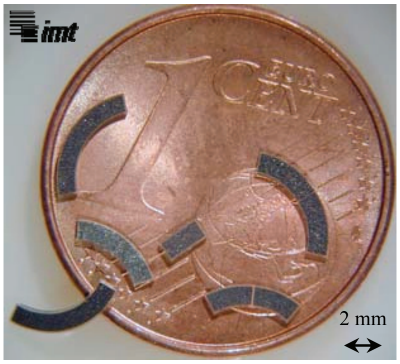

Fig.5: Photograph of microfabricated polymer magnets.

Obtained magnets need to be magnetized in order to define their magnetization direction. For such purposes, special magnetization equipment was designed at the IMT in order to magnetize the polymer magnets in axial direction [11]. Adapters with configurations similar to the magnet shape were also designed and manufactured using precision mechanics to ensure high magnetization performance.

The magnetic properties of fabricated polymer magnets (Fig. 6) are then characterized using a vibrating sample magnetometer (LakeShore Inc.) for 90 %wt powder ratio at structure height of 389 µm.

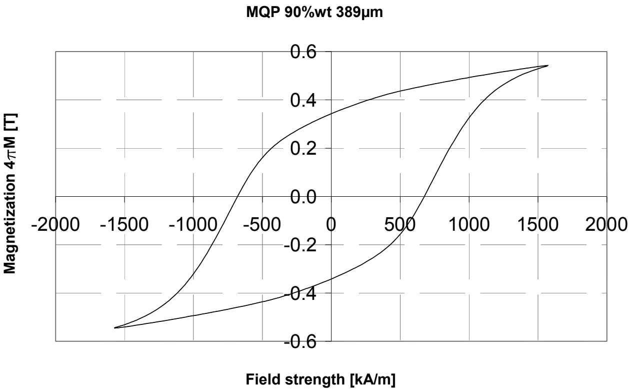

Fig. 6: magnetization characteristic of the fabricated polymer magnets

3.3 Glass Cover

For the cover, a glass substrate of 700 µm thickness is used. On both sides of the substrate a gold layer is deposited and then coated with AZ9260. The AZ photoresist and the gold are patterned successively providing the openings for the inlet and outlet. These vents are etched from both sides simultaneously in the glass substrate with a dilution consisting of water, phosphoric acid and hydrofluoric acid. After that, the covers are separated by wafer dicing and the AZ as well as the gold layer are removed from substrate.

4 RESULTS AND DISCUSSION

The validity of proposed concept has been first tested in a meso-scale pump [3]. Experiments showed that the flow rate changes nearly linearly with rotational speed and a maximum volumetric flow rate of 13.7 ml/min at 200 rpm (Fig. 7) was obtained at channel width and height of 2 mm. This quantity of flow rate can be increased by using curved magnets instead of the linear magnet employed in the experiments which caused a high rate of internal leakage (between the magnets and channel walls).

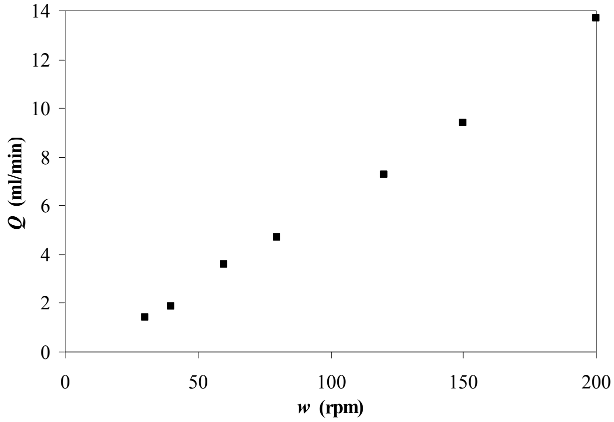

Fig. 7: Volumetric flow rate against rotational speed

Obtained results are motivating and encouraged further miniaturization of the pump dimensions. However, to achieve micropumping effect, the actuator chip should be initially optimized for a wide range of parameters, including investigating the micro coils, gap between the fluidic channel and polymer magnets (tolerances), and energization schemes. For microcoils, an analytical model that studied the effect of coil operating and geometrical parameters, current, number of turns and gap between turns, has been developed [14]. Results showed that the microcoil design parameters have critical values that can be calculated for each design using developed analytical model.

As for fluidic gap (tolerance), several values ranging from 50 µm to 150 µm have been investigated. Results showed that low gap values result in high friction forces that exceed the electromagnetic force generated between the coils and the magnet and no movement can be achieved. To overcome this problem, water was dispensed in the channel to reduce the friction forces. The actuator capability to move one magnet through the annular channel was tested. It has been found that higher gaps result in smoother magnet movement. However, this will reduce the pump efficiency and increase the internal leakage.

Regarding energization schemes, it has been found that simultaneous control of energizing two coils in steps, one attracting the magnet from the front side and the other repelling it from the back side, results in a rotating action. During tests the current values were changed between 50 and 200 mA and the coils energization time step (rotational speed) was changed between 10 and 200 ms. A maximum rotational speed of about 600 rpm was obtained at 200 mA. Increasing the speed needs to increase the current and damage to the coils may occur.

Further the energization scheme was modified to apply moving and holding action on a magnet within the rotation cycle (i.e., the magnet is first accelerated from coil C1 and then decelerated to stop again in C1 within one cycle and so on). Results showed also the possibility of controlling this action.

Finally the energization scheme was developed to control the rotation of two magnets within the fluidic channel. Observations showed that the magnet attracted to the holding coil slips due to the water pressure exerted by the moving coil. This means higher electromagnetic forces are needed to create pumping action and further improved designs should be tested.

5 CONCLUSIONS

In this work, the concept of a newly proposed electromagnetic micropump was presented. Successful tests were performed on a circular actuator to rotate one magnet. A maximum rotational speed up to 600 rpm is obtained in a fluidic channel of 380 μm height and 1500 μm width. Further visualization experiments showed that the electromagnetic force between the magnets and coils is still not large enough to employ pumping action and optimization of the coils and magnets strengths are required.

6 ACKNOWLEDGMENT

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