PLASTIC MICROPUMPS USING FERROFLUID AND MAGNETIC MEMBRANE ACTUATION

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ABSTRACT

This paper presents a simple and low-cost prototyping technology for the realization of integrated micropumps in polymethylmethacrylate (PMMA). The three-dimensional (3D) micropumps consist of stacks of structured PMMA layers, which are either realised with precision milling tools for the more complex parts, or fabricated using the powder blasting technique for channel-type structures. We integrate silicone membranes into the chip to realize check-valves or use dynamic diffuser valves. We use two different types of magnetic actuation external to the micropump: (i) an external magnet displaces a ferrofluid liquid plug that plays the role of a piston in a channel; (ii) an external coil actuates an integrated magnetic membrane, consisting of NdFeB magnetic powder in a polydimethylsiloxane (PDMS) matrix.

1. INTRODUCTION

One can report several papers dealing with the use of magnetic actuation principles for microfluidic system applications, and more specifically for use in micropumps [1-5]: both ferrofluid columns [1,2] and electromagnetically actuated magnetic membranes [3-5] have been presented. However, these micropumps were based either on silicon technology or had the actuation coil integrated within the pump, disabling their use for cheap and disposable Lab-on-a-Chip applications.

We present two different types of magnetically actuated micropumps realised out of PMMA plastic using powder blasting microfabrication and conventional precision machining. Both types of pump are externally actuated in order to avoid an expensive all-in integrated system. Valving principles are also investigated through two different designs: check-valves having a corrugated silicone membrane are used for the ferrofluid actuated micropump, while nozzle/diffuser elements are integrated in the magnetic membrane actuated micropump.

2. MICROFABRICATION TECHNOLOGY

Both types of micropumps are fabricated out of 36 mm x 22 mm PMMA plates and sheets having a thickness of 250 µm, 1 mm and 2 mm, respectively. Complex parts are machined with precision milling tools, while the powder blasting technique is used to realize planar microfluidic structures. This rapid prototyping method offers an efficient solution for the fabrication of fluidic devices, with minimum channel dimensions down to 100 µm. In a first step, a metallic mask resistant to powder blasting is realised by laser cutting. Using this mask, fluidic structures are micropatterned by the action of accelerated alumina (Al_2O_3) particles on 250 µm thick PMMA sheets. This thickness determines the microfluidic channel depth. The different layers are then assembled into a monolithic 3D microfluidic structure by an appropriate chemical binding method. The assembly step is realised in a hot press and only takes a few minutes.

3. FERROFLUID ACTUATED MICROPUMP

Check-valve integration

A corrugated silicone membrane with an external diameter of 7 mm is integrated into the chip to realize the check-valve. The valve requires the presence of a PMMA pillar structure in a cavity, which is machined using standard milling tools (see Fig. 1).

Ferrofluid piston actuation

The ferrofluid micropump consists of an hermetically sealing ferrofluid plug inside a 1 mm^2 channel and two silicone corrugated check-valves that are tightly fixed between PMMA plates. Our prototype is constituted of 7 PMMA layers, as illustrated in the 3D burst view represented in Fig. 2.

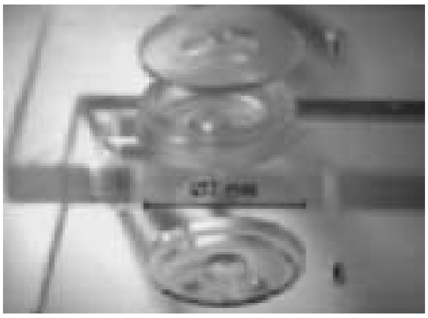

Figure 1 : Burst view of a check-valve showing the corrugated silicone membrane (Ø = 7 mm) between two micromachined PMMA plates.

(a)

(b)

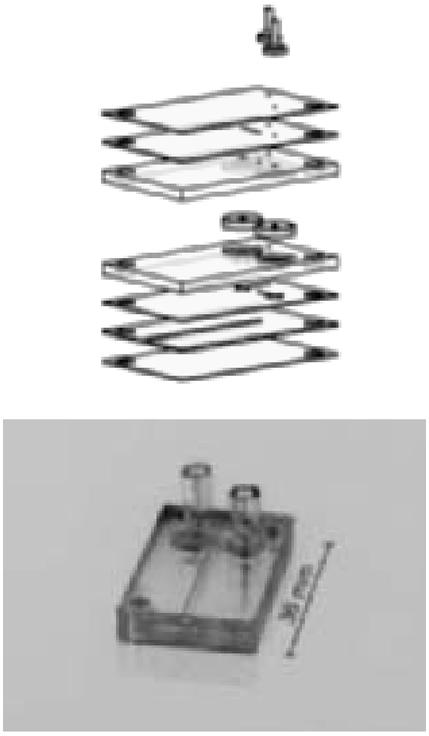

Figure 2 : Burst view and photograph of the ferrofluid micropump [36 mm x 22 mm x 5 mm].

We use an in-house developed water-based ferrofluid, which is a colloidal suspension of magnetic nanosized particles having a saturation magnetization of 30 mT. The ferrofluid plug is magnetically moved with an external magnet (NdFeB, diameter 10 mm, height 4 mm) that is displaced linearly using a motorised precision stage.

Experimental results

Measurements are done as a function of different hydrostatic backpressures, obtained by adjusting the height of a capillary tube placed at the outlet (see Fig. 3). The various pressure-flow characteristics are reported in Fig. 4. The maximum flow rate measured is about 30 microliters per minute, and a maximum backpressure close to 25 millibars is achieved with our ferrofluid. For a more complete description of the ferrofluid actuated pump, we refer to [6].

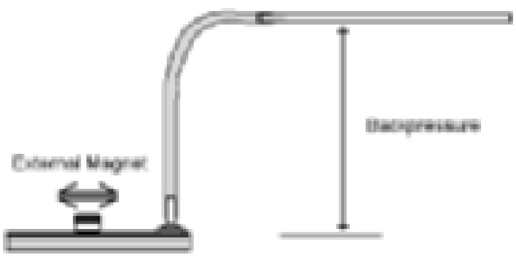

Figure 3 : Magnetic actuation principle of the ferrofluid piston micropump with an external magnet.

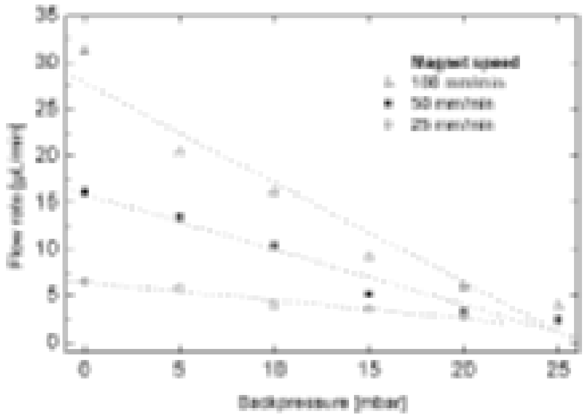

Figure 4 : Pressure-flow characteristic of the ferrofluid micropump for water pumped with different speeds of the rare-earth magnet.

4. Magnetic Membrane Actuated Micropump

The magnetic diaphragm based micropump uses the reciprocating effect of a flexible, magnetic powder containing membrane in combination with two nozzle/diffuser elements (see Fig. 5). The magnetic membrane is externally actuated by an electromagnet.

Nozzle/diffuser valving

The working principle of a diffuser-based pump was first presented by Stemme et al. [7]. Nozzle/diffuser elements are fluidic channel constrictions that modify the fluid dynamics. The directional effects that characterize these elements enable the fabrication of valveless micropumps. The simple design of the valving elements facilitates the microfabrication in the PMMA sheets by powder blasting and limits the number of layers necessary for the realization of the pump. A photograph of one of the realized diffuser elements is shown in Fig. 6.

Electromagnetic actuation

A NdFeB composite membrane is fabricated using a two step moulding technique. The magnetic powder is first mixed with PDMS to synthesize a rare-earth polymer magnet which is integrated on top of a larger PDMS membrane. After polymerisation of the PDMS, the magnetic membrane is magnetized in an electromagnet before being integrated in the chip. The membrane is externally actuated by a 1500 turns coil supplied with a sinusoidal current of 150 mA amplitude (see Fig. 7).

(a)

(b)

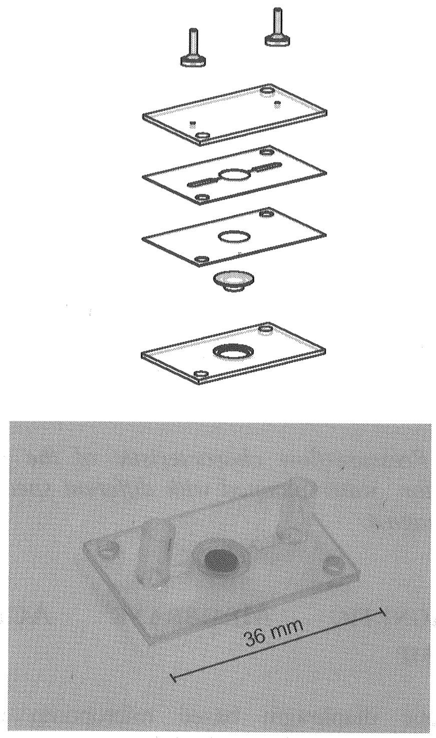

Figure 5 : (a) 3D view of the magnetic membrane valveless micropump, and (b) Photograph of the micropump.

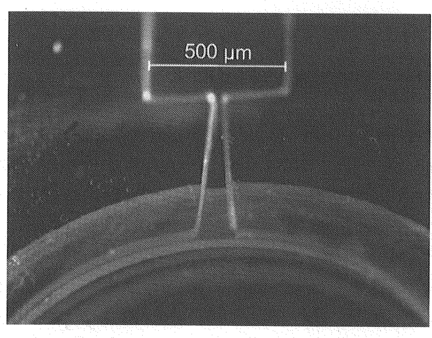

Figure 6 : Photograph of the diffuser element.

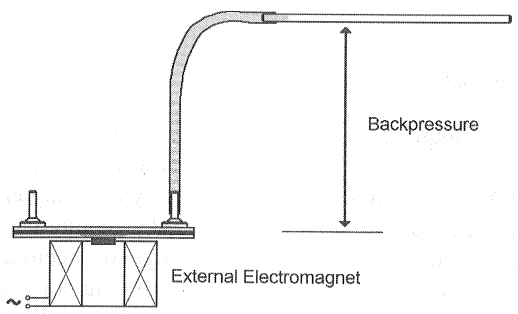

Figure 7 : Electromagnetic actuation of the diaphragm micropump.

Experimental results

The valveless diaphragm micropump is an oscillatory liquid circuit, for which we assume that the rigidity of the membrane and the inertia of the fluid in the nozzle/diffuser elements dominate the resonance frequency. In such approximation, Olsson et al. [8] have determined the resonance frequency f_0 of the system:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{K_p\left(1+\sqrt{\eta}\right)^2 b\,(D-d)}{\rho K_v (1+\eta) L \ln\frac{D}{d}}} \qquad (1)$$

with as parameters the diffuser depth $b = 250$ µm, diffuser inlet width $d = 100$ µm, diffuser outlet width $D = 500$ µm, diffuser length $L = 2.3$ mm and density of water $\rho = 1000$ kg/m^3. By monitoring the membrane deflection as a function of pressure, the membrane stiffness is measured to be $K_p = 6$ MPa. K_v is the ratio of the volume variation amplitude to the deflection of the membrane at the centre, which we estimate to be $1.96\ 10^{-5}\ m^2 < K_v < 3.85\ 10^{-5}\ m^2$. $\eta \approx 2.5$ is the efficiency ratio of the diffuser element, the value of which we obtained through numerical simulation. The resonance frequency calculated with (1) is estimated to be 14 Hz $< f_0 <$ 20 Hz for water, which is in good agreement with the measured resonance frequency of the diaphragm micropump, which is about 12 Hz (see Fig. 8). Dissipative effects in the silicone membrane and the fluid resistance of the microchannels are both responsible for the damping effect.

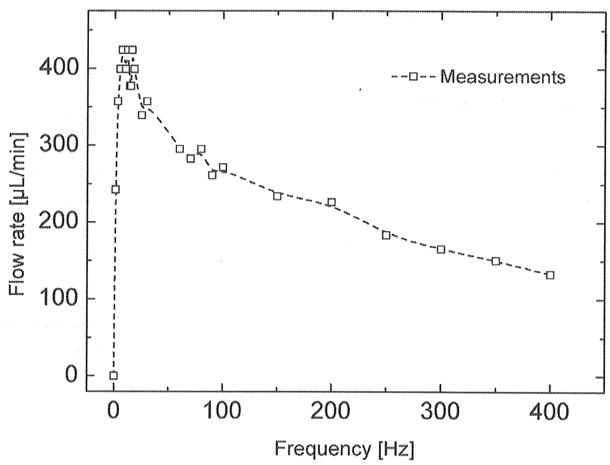

Figure 8 : Actuation frequency dependence of the flow rate for water for the valveless micropump. The response curve is similar to that of a damped mass-spring system. The dashed curve is a guide to the eye.

In Fig. 9, we report the experimental measurements of the pressure-flow characteristic for water at three different frequencies, including the response for a frequency close to the resonance.

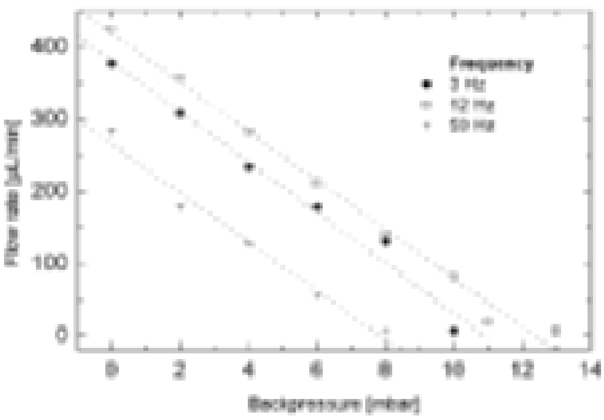

Figure 9 : Pressure-flow characteristic of the valveless micropump for water pumped at different frequencies.

5. CONCLUSION

The characterization of the two types of micropump shows the potential of external magnetic actuation methods in combination with disposable microsystems. For both pump types, water has been successfully pumped at different flow rates up to 400 µL/min. The maximum backpressure of 25 mbar obtained with the ferrofluid pump is of the best reported so far. A 12 mbar backpressure has been achieved with the diaphragm micropump. The choice for a cheap and disposable plastic chip in combination with a permanent external magnetic actuation system seems promising for future disposable Lab-on-a-Chip applications.

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