



A Magnetic Micropump Based on Ferrofluidic Actuation

Lung-Ming Fu^{1,2}, Wei-Ching Fang¹, Ting-Fu Hong^{1,3,*},
and Chia-Yen Lee^{1,3,*}

¹ Graduate Institute of Materials Engineering, National Pingtung University of Science and Technology, Taiwan

² Department of Biomechatronics Engineering, National Pingtung University of Science and Technology, Taiwan

³ Department of Vehicle Engineering, National Pingtung University of Science and Technology, Taiwan

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*Corresponding author: tfhong@mail.npust.edu.tw; leecy@mail.npust.edu.tw

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Abstract: A circular ferrofluidic micropump for biomedical applications is proposed comprising two ferrofluidic plugs contained within a PMMA (Polymethyl-Methacrylate) microchannel and driven by a rotating stepping motor. Orthogonal and tangent-type micropumps are developed. The circular ferrofluidic micropump chip is patterned using a commercially-available CO₂ laser scriber. The operation of the micropump relies on the use of magnetically-actuated ferrofluidic plugs. The ferrofluid contacts the pumped fluid but is immiscible with it. The flow rate in the two types of proposed devices can be easily controlled by adjusting the rotational velocity of the stepping motor. Results show that a maximum flow rate of 128 $\mu\text{l}/\text{min}$ is obtained using the tangent-type micropump with a channel width of 1000 μm and a rotational velocity of 10 rpm with zero pressure head.

Keywords: ferrofluidics; microfluidics; micropump

Introduction

Rapid advances in the field of micro-total-analysis-systems (μ -TAS) have included the development of a wide variety of microfluidic devices for use in the industrial, chemical, biological and medical domains [1-5]. These devices have emerged as a powerful toolset for miniaturization, reducing power consumption, reducing sample and reagent use, improving sensitivity, improving efficiency, reducing processing times, increasing portability, and allowing for integration with other miniaturized devices. Several functional microfluidic devices have been developed to perform a variety of tasks, including sample pre-treatment and injection, micropumps, micromixers, micro distillation, polymerase chain reactions (PCR), and cell/particle separation and counting [6-15].

Many alternative actuation mechanisms have been proposed to achieve a pumping effect in microfluidic devices, including acoustic-wave-based, rotary,

piezoelectric, thermopneumatic, electrostatic, electromagnetic and ferrofluidic methods [16-21]. Recently, Lee's group [22-25] developed an impedance-based micro pump based on electromagnetic actuation and including a copper microcoil, a glass microchannel, a glass cover plate and a PDMS diaphragm with a magnet mounted on its upper surface. In their study, fluid was driven through the pump by applying a current to the micro coil such that an electromagnetic force was established and resulted in a deflection of the PDMS diaphragm. The performance of the pump showed that the maximum diaphragm deflection was 110 μm when applying an actuating current of 0.6 A, and a flow rate of 7.2 ml/min could be achieved by driving the diaphragm at a frequency of 200 Hz.

Hsu and Sheen [26] presented a microfluidic flow-converter based on a double-chamber planar micropump. The flow measurements using micro-PIV clearly demonstrated the process of how oscillatory flows were converted into a smooth continuous flow in anti-phase mode operation. Based on the flow rectifying



capability and conversion ratio, the pumping performance and flow quality were found to possess optimal values when the operation frequencies were in the range of 0.2–0.8 kHz. Ogawa *et al.* [27] presented a valveless liquid pumping device by inducing traveling waves beneath the ceiling wall induced by applying sinusoidal voltages with a phase difference of $2\pi/3$ to adjacent top electrodes. When a channel wall oscillates in the form of traveling waves, peristaltic motion is induced and the liquid beneath the wall moves along an elliptic curve. After a period of oscillation, the fluid moves slightly forward from the initial position due to fluid viscosity. Fadl *et al.* [28] presented a multifunction and bidirectional valve-less rectification micropump based on bifurcation geometry. Results showed that the double-generation bifurcation design outperforms the single-bifurcation design, and the hybrid bifurcation design was associated with the highest flow rate (137 $\mu\text{l}/\text{min}$), maximum back pressure (2.86 kPa), and pump efficiency (23.25). Mishchuk *et al.* [29] presented a microfluidic pump based on the phenomenon of electroosmosis of the second kind. The experimental results showed an approximately second order dependence of flow velocity and pressure on the applied voltage, as predicted from the theory of electroosmosis of the second kind. Zhu *et al.* [30] proposed a technique for focusing microparticles using stable magnetic nanoparticles suspension (ferrofluid) by exerting magnetic buoyancy forces on non-magnetic particles within ferrofluids under a non-uniform magnetic field. In this way, they focused 4.8, 5.8 and 7.3 μm microparticles at various flow rates in a microfluidic channel.

Figure 1 shows a schematic illustration of the current circular ferrofluidic micropump. The device includes an input nozzle, a circular microchannel, an output nozzle, two ferrofluidic plugs, and an external

permanent magnet mounted on a simple stepper motor mechanism (K27, AVIOSYS, Taiwan). The present study develops two types of ferrofluidic magnetic micropumps (i.e. orthogonal and tangent types) comprising two ferrofluidic plugs contained within a circular PMMA microchannel and an external permanent magnet positioned beneath one of the ferrofluidic plugs and driven by a rotating stepping motor. One of the ferrofluidic plugs can be attracted by the permanent magnet. As the permanent magnet rotates with the stepping motor, the ferrofluidic plug rotates and the sample fluid and the other ferrofluidic plug are caused to rotate together in the circular microchannel. Therefore, as the ferrofluidic plug above the external magnet rotates, fluid is driven out of the pump via the outlet channel, while new sample fluid is simultaneously drawn into the pump through the inlet channel. Thus, a continuous pumping effect is achieved. The maximum flow rate (128 $\mu\text{l}/\text{min}$) with zero pressure head is evaluated experimentally at a rotational speed of 10 rpm and a channel of 1000 μm in the tangent-type micropump.

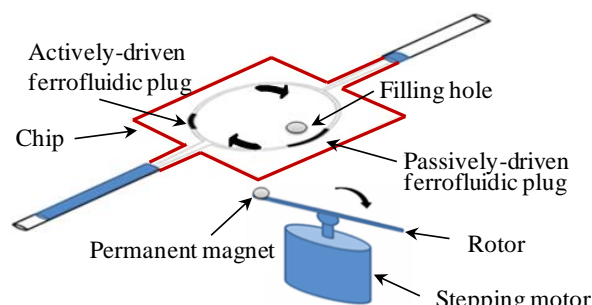


Figure 1. Schematic illustration of circular ferrofluidic micropump.

Design and Fabrication

The pumping mechanism relies on magnetic actuation to move a ferrofluidic plug that pushes and/or pulls the fluid of interest (Figure 1). A ferrofluid contains oil-based Fe_3O_4 nano-particles suspended in an aqueous solvent (EMG 901, saturation magnetization value: 600 G; viscosity: 10 cP). For the pumping application, the ferrofluid must be immiscible with the fluid being pumped. The ferrofluid was retained in the pump chamber during operation, while the fluid of interest was pumped through the device.

A closed-loop configuration was chosen for continuous pumping (Figure 2). A circular geometry was used for easy implementation of the moving magnetic actuator. In the configuration, two nozzles were located as the inlet and outlet of the pumping loop to induce the pumping function, and the ferrofluid acts as both a piston and a valve. A ferrofluidic plug serving as a piston is drawn around the channel by translating the magnetic

Lung-Ming Fu received his PhD in Engineering Science from National Cheng Kung University, Taiwan in 2001. He currently serves as professor in the Graduate Institute of Materials Engineering at National Pingtung University of Science and Technology. His research interests include microfluidic systems, MEMS fabrication technologies, micro-sensors and computational fluid dynamics.

Wei-Ching Fang is currently a graduate student in Materials Engineering at National Pingtung University of Science and Technology (NPUST), where he is developing microdevices for the detection of food additives.

Ting-Fu Hong received his PhD in Materials Science from the University of London (UK) in 2006. He is currently an associate professor in the Graduate Institute of Materials Engineering at National Pingtung University of Science and Technology. His research interests include functional surface treatments on metallic biomaterials, synthesis of micro-nano metallic and ceramic particles, and MEMS fabrication technologies.

Chia-Yen Lee received his PhD degree from the Department of Engineering Science at National Cheng Kung University, Taiwan in 2004 after a career in industry. He currently serves as professor in the Department of Vehicle Engineering at National Pingtung University of Science and Technology, Taiwan. His research interests focus on the development of micro-sensors and micro-actuators.



field, in this case generated by an external magnet attached to the rotor of a stepping motor. As the mobile plug is drawn around the pumping loop, fluid is drawn into the pumping loop through the inlet, and forced out through the outlet. If the mobile plug is stopped, it also serves as a valve.

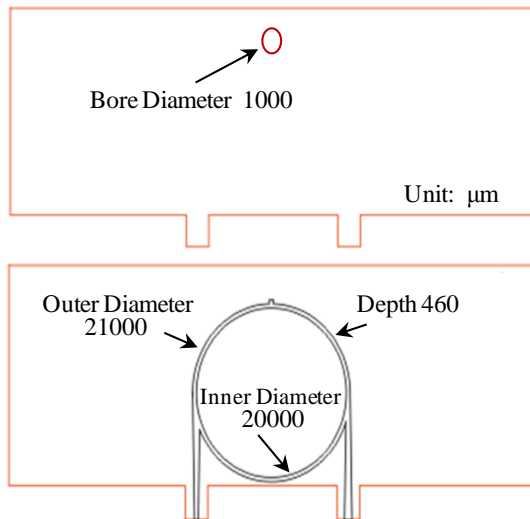


Figure 2. Layouts of upper and lower substrates of micropump.

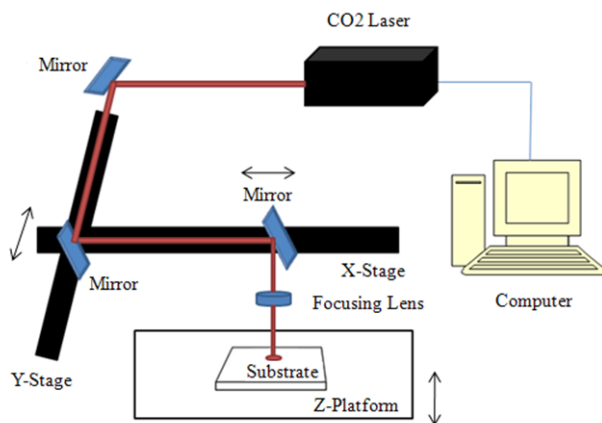


Figure 3. Schematic illustration of CO2 laser ablation system used to pattern PMMA substrates.

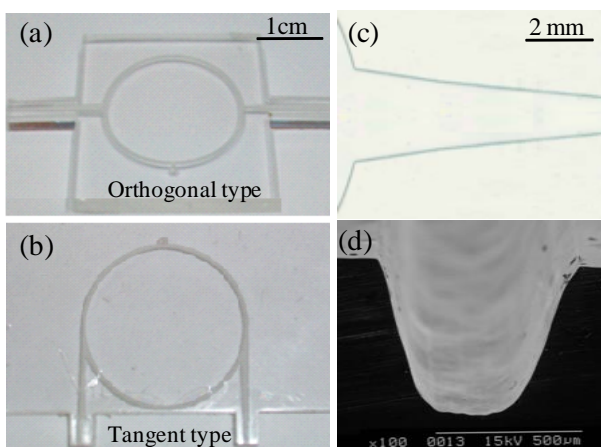


Figure 4. Photographs of fabricated micropumps: (a) orthogonal, (b) tangent types, (c) one example of the nozzle/diffuser, and (d) microchannel cross-section.

The microchannel configuration of the micropump was designed using commercial AutoCAD (2011) software and was then converted into a machining pattern via Corel Graphics Suite 11 software. The microchannels were etched into PMMA substrates using a VII-12 CO₂ laser system (Giant Technologies Incorporated), operated in a continuous mode with a maximum power output of 12 W and a wavelength of 10500 nm (Figure 3). Prior to the ablation process, etching trials were performed using a defocused laser beam (the defocused laser beam ablation method is described in detail in [31]). Finally, the two substrates of the micropump device were bonded using hot bonding techniques. Figures 4(a) and 4(b) respectively present photographs of the circular loops with the orthogonal and tangent-type micropumps. Figures 4(c) and 4(d) respectively present an example of the nozzle/diffuser and microchannel cross-section.

Results and discussion

Figure 5 shows a photograph of the circular ferrofluidic pump system. After filling the channel with water, two plugs were separately introduced to the channel via the filling hole as the permanent magnet attract them to the specified section in the channel. In evaluating micropump performance, the stepping motor was run continuously in the clockwise direction at a constant speed in the range of 2 ~ 10 rpm.

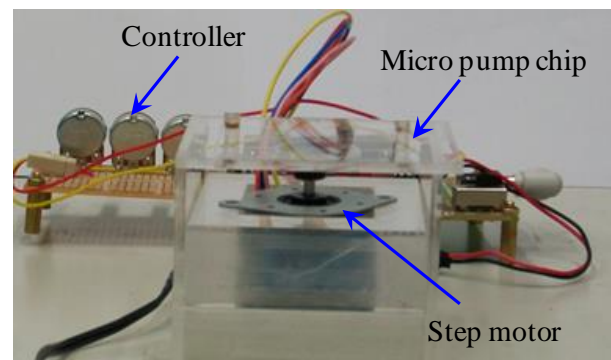


Figure 5. Photograph of circular ferrofluidic pump system.

Figure 6 shows the variation of the flow rate (Q) with a channel width of 500 μm with zero pressure head for motor velocities of 2 ~ 10 rpm in the orthogonal and tangent-type micropumps. The corresponding flow rate was then calculated as $Q=VA=V*\pi D^2/4$, in which V is the flow velocity and D is the diameter of the tubing. In general, it is seen that the flow rate increases with motor velocity. In addition, it is observed that the flow rate of the tangent micropump is slightly higher than that of the orthogonal one at a constant motor velocity due to the reduced pipe loss of the tangent-type microchannel. As

shown in Figure 6 (corresponding to a rotational speed of 10 rpm), a maximum flow rate of 68 $\mu\text{l}/\text{min}$ was obtained with zero pressure head.

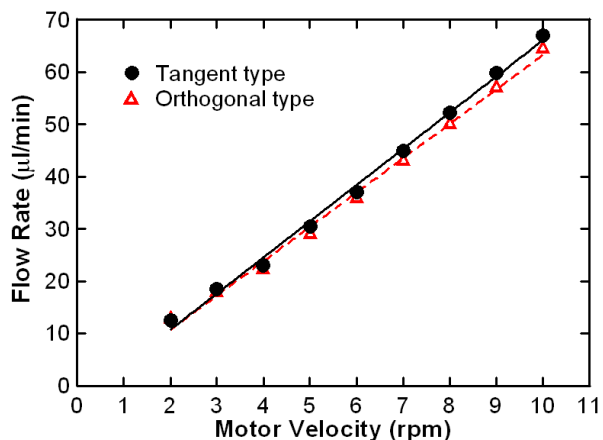


Figure 6. Variation of maximum flow rate with different motor velocities at a channel width of 500 μm for the different microchannel types.

Figure 7 shows the variation of maximum flow rate with different motor velocities at different channel widths for both types of micropump. The flow rate increases with motor velocity given a circular channel with a constant width. The flow rate also increases with channel width because the wider channel reduces pipe loss. The proposed device achieves maximum flow rates of 127 $\mu\text{l}/\text{min}$ and 128 $\mu\text{l}/\text{min}$, respectively, for the orthogonal and tangent-type micropumps, given a channel width of 1000 μm and a stepping motor velocity of 10 rpm. The flow rates of the tangent micropump are almost equal to those with the orthogonal type due to there are no head pressure loss.

Conclusions

Two types of circular ferrofluidic PMMA-based micropumps (orthogonal and tangent types) were designed and fabricated incorporating magnetically-actuated ferrofluidic plugs and a permanent

magnet rotated by a stepping motor. Both micropumps were easily and cheaply patterned using a commercial CO_2 laser system and thermal bonding techniques. Experimental results show that the pumps allow flexible control of the flow rate, and can be excited by a low rotational velocity of the stepping motor. In addition, for both micropumps with a given rotational velocity, the flow rate can be improved by increasing the circular channel width. The proposed device achieves maximum flow rates of 127 $\mu\text{l}/\text{min}$ and 128 $\mu\text{l}/\text{min}$, respectively, for the orthogonal and tangent-type micropumps, with zero pressure head given a channel width of 1000 μm and a stepping motor velocity of 10 rpm. The maximum flow rate is very similar for both micropump types because there is no head pressure loss. Overall, experimental results indicate that the proposed micropumps represent a good solution for microfluidic systems which require flexible pumping control.

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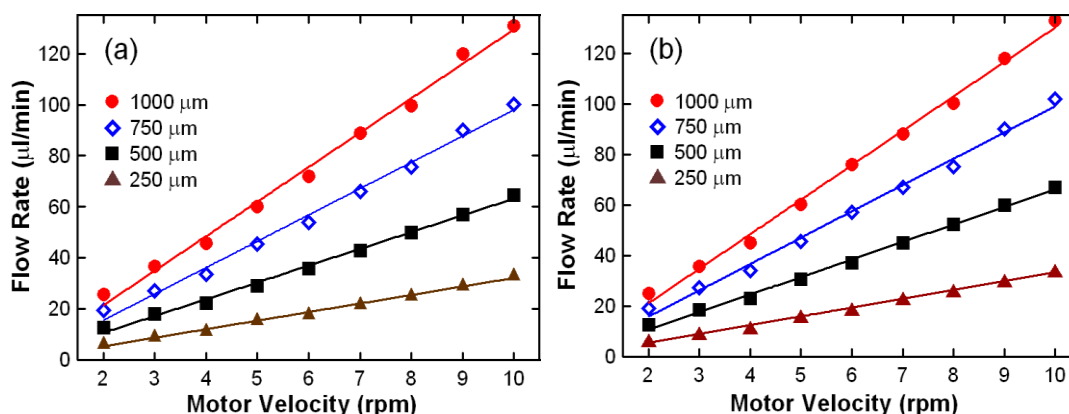


Figure 7. Variation of maximum flow rate with different motor velocities and channel widths: (a) orthogonal and (b) tangent-type micropumps.

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