

Multifunctional microvalves control by optical illumination on nanoheaters and its application in centrifugal microfluidic devices†

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Valving is critical in microfluidic systems. Among many innovative microvalves used in lab-on-a-chip applications, phase change based microvalves using paraffin wax are particularly attractive for disposable biochip applications because they are simple to implement, cost-effective and biocompatible. However, previously reported paraffin-based valves require embedded microheaters and therefore multi-step operation of many microvalves was a difficult problem. Besides, the operation time was relatively long, 2–10 s. In this paper, we report a unique phase change based microvalve for rapid and versatile operation of multiple microvalves using a single laser diode. The valve is made of nanocomposite materials in which 10 nm-sized iron oxide nanoparticles are dispersed in paraffin wax and used as nanoheaters when excited by laser irradiation. Laser light of relatively weak intensity was able to melt the paraffin wax with the embedded iron oxide nanoparticles, whereas even a very intense laser beam does not melt wax alone. The microvalves are leak-free up to 403.0 ± 7.6 kPa and the response times to operate both normally closed and normally opened microvalves are less than 0.5 s. Furthermore, a sequential operation of multiple microvalves on a centrifugal microfluidic device using a single laser diode was demonstrated. It showed that the optical control of multiple microvalves is fast, robust, simple to operate, and requires minimal chip space and thus is well suited for fully integrated lab-on-a-chip applications.

1. Introduction

During the last two decades, research in the area of lab-on-a-chip (LOC) has dramatically increased.^{1–5} To successfully execute integration of analytical steps such as mixing, separation and reaction on chip, microvalves play an important role in the LOC system. However, simple and reliable microvalves have not yet been fully developed despite rigorous efforts from many groups.^{6–8}

One of the attractive microvalves that has been implemented in lab-on-a-chip devices is the phase change based microvalve. Various kinds of materials such as hydrogel,^{9–14} sol–gel,¹⁵ paraffin,^{16,17} and ice¹⁸ that can undergo a phase transition from solid to liquid in response to changes in temperature have been investigated. For example, Kellogg *et al.* used a wax valve on a centrifugal microfluidic platform.¹⁹ Liu *et al.*¹⁶ developed an integrated device for pathogen detection using paraffin microvalves, taking advantage of its simplicity and biocompatibility.

Although these innovative phase transition valves offer many advantages, they also suffer from several shortcomings. First, because these require embedded microfabricated heaters, the size of the valve is relatively large. Consequently, multiple microvalves could not be located nearby because of the heat

transfer issues. As a result, the design of the electrode connection lines and the control of individual microheaters for each microvalve operation could be a difficult problem if the operation of many valves is necessary in order to perform multi-step analytical procedures.

Second, the operation time required to open and close the paraffin microvalve is relatively long compared to that of other mechanical or pneumatic microvalves, *i.e.* in the range of 2–10 s. Lastly, to close channels using paraffin microvalves, a structure for an air pocket was necessary, which requires additional chip space.¹⁶

Here, we report a unique phase change based microvalve for rapid and versatile operation of multiple microvalves using single laser diode. The valve is made of nanocomposite materials in which 10 nm-sized iron oxide nanoparticles are dispersed in paraffin wax. Laser light of relatively weak intensity was able to melt the paraffin wax with embedded iron oxide nanoparticles, whereas even a very intense laser beam does not melt wax alone. This is based on the strong absorption of laser light by iron oxide nanoparticles. Using the mechanism of melting paraffin wax matrix with embedded nanoparticles by optical excitation, the response time to open the valve was determined to be 12 ms.

We previously demonstrated a simple and rapid DNA extraction method by using a 808 nm laser and carboxyl-terminated magnetic beads.²⁰ The laser beam is effectively transmitted to the magnetic beads, and highly heated magnetic beads transfer the thermal energy to the solution.

In the proposed novel microvalve concept of Laser Irradiated Ferrowax Microvalves (LIFM) as shown in

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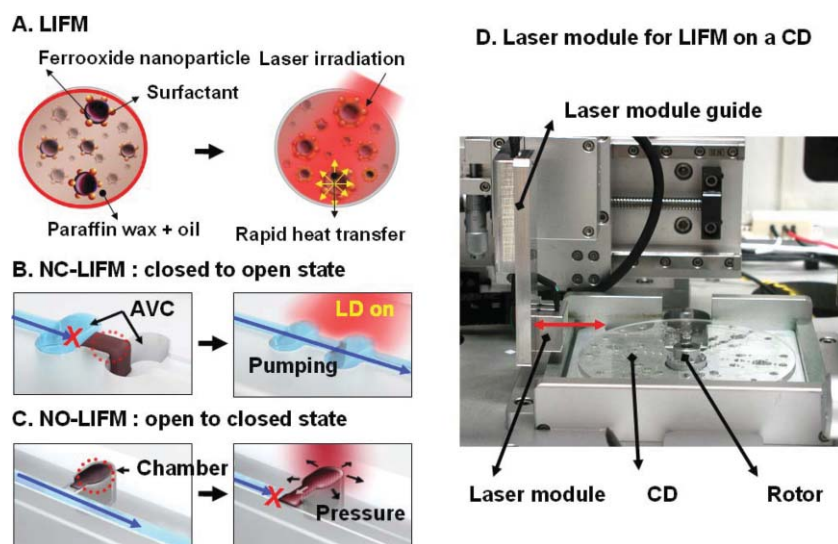


Fig. 1 Schematic diagram of LIFM operation. (A) The principle of LIFM. Highly heated nanoparticles by laser irradiation transferred heat energy to paraffin wax around the nanoparticles, resulting in accelerated melting. (B) Ferrowax plug for NC-LIFM is formed in the capillary between two AVCs. As laser power is applied, the molten ferrowax flows to the AVC, solidifies, and results in the main channel being opened. (C) In order to block the fluid passage, the ferrowax chamber located adjacent to the main channel is preloaded with ferrowax. As the ferrowax is heated by laser irradiation, the molten ferrowax bursts into the main channel and immediately solidifies and blocks the channel. (D) A photograph showing the experimental set-up for the centrifugal microfluidics and the laser diode motion control unit.

Fig. 1A, magnetic nanoparticles are dispersed in paraffin wax and used as nanoheaters when excited by laser irradiation. Fig. 1B and C show the basic concept of opening the Normally Closed LIFM (NC-LIFM) and closing the Normally Opened LIFM (NO-LIFM), respectively. To open the NC-LIFM, the laser beam is focused at the valve location and the molten ferrowax flows to the Assistant Valve Chamber (AVC) and solidifies, and results in the main channel being opened as shown in Fig. 1B. To block the channel, the laser beam is focused at the pre-loaded ferrowax chamber located adjacent to the main channel. Upon laser irradiation, the pressure of the pre-loaded ferrowax chamber increases and the molten ferrowax bursts into the main microchannel and blocks the channel as shown in Fig. 1C. As a result, rapid operation of many LIFMs is possible using only a single laser diode without the need of fabricating many embedded microheaters. Fig. 1D shows the experimental set-up for the laser-diode motion control unit and the rotor.

Nanoparticles have great potential in many biological applications. For example, semiconductor nanoparticles have been used as fluorescence markers.²¹ In general, metal nanoparticles do not have strong fluorescence emission, however, useful thermal properties have been reported.^{22–24} They generate heat efficiently when excited by laser irradiation. Using this phenomenon, Skirtach *et al.*²² described the remote control of drug release from a capsule containing Au nanoparticles by optical excitation. Cognet *et al.*²³ imaged protein labeled with Au nanoparticles in cells using photo-thermal interference contrast.

Richardson *et al.*²⁴ optically excited Au nanoparticles embedded in an ice matrix and investigated the mechanism of heat generation and the melting process. Au nanoparticles were mostly trapped at the grain boundaries and do not exist in the form of single nanoparticles but form small complexes of

various geometries. The threshold melting power required to melt ice had a strong correlation with the density of nanoparticles. When many Au nanoparticles formed a complex and the laser beam was focused at the position with a large density of Au nanoparticles, the ice melted with the light source even with very weak intensity.

A previous study by Herb *et al.*²⁵ used hydrocarbon–fluorocarbon–oil based ferrofluidic microvalves actuated by a permanent magnet. The position of the valve was controllable and also the single valve was reusable both for closing and opening purposes. However, these ferrofluidic microvalves could resist the hydrodynamic pressure only up to 12 kPa under a magnetic field of 2.8 kG.

Oh *et al.*²⁶ used “Ferrowax” (the mixture of ferrofluid and paraffin wax) microvalve in order to increase the hold-up pressure, however, microfabricated microheaters and permanent magnets were still used for the actuation of microvalves.

In this report, we also used the phase transition of the ferrowax for the valving mechanism; however, only a single laser diode was used instead of many microfabricated heaters and magnets. As a result, it becomes very simple to control multiple microvalves. We have demonstrated the operation of multiple microvalves on a centrifugal microfluidic platform by using a single laser diode. In addition, the response time to actuate microvalves was accelerated because the laser beam effectively heats the iron oxide nanoparticles embedded in the paraffin wax matrix. To the best of our knowledge, it is the first use of optical excitation of nanoparticles for the mechanism of microvalve operation. Because it is fast, robust, cost-effective, biocompatible, and simple to implement for the control of multiple microvalves on a chip, it could be a key component to realize fully integrated lab-on-a-chip devices.

2. Materials and methods

2.1 Preparation of LIFM

As shown in Fig. S1A, the polycarbonate (PC) test chip is composed of a top layer consisting of various inlet holes and a bottom layer consisting of channels and chambers (see the Electronic Supplementary Information (ESI)). The channel width was 1 mm and the depth was 100 μm . The depth of the chamber was 3 mm. The inlet holes and channels were produced by a conventional Computer Numerical Control (CNC) machine (Sirius 550, Hwacheon Inc., Korea), and the two separate layers were bonded by adding 20 μL of acetone to the solvent injection hole and moved *via* capillary action through the solvent channel.²⁷ The distribution of acetone through the gaps in the fluidic channel, chamber and the solvent channels resulted in a permanent bonding.

CD type microfluidic devices are made of polycarbonate (PC) plates bonded with a double sided adhesive tape (Flexmount DFM 200 Clear V-95 150 POLY H-9 V-95 4, FLEXcon Inc., MA, USA). The microfluidic layouts designed by using CAD (Computer-Aided Design) were cut by using a computer controlled vinyl film cutter (CE2000-60, Graphtec).²⁸

Ferrowax consists of paraffin wax (T_m 50–52 $^{\circ}\text{C}$, Fluka Chemie, GmbH) and ferrofluid (APG 314, Ferrotec Inc., CA, USA). Molten ferrowax is much less viscous than molten paraffin wax and thus injection of the wax material to the desired position is much easier. The compositions of the ferrofluid are hydrocarbon based carrier oil (77–92%), nano-sized iron oxide molecules (1–5%), oil soluble dispersant (6–16%), and oil soluble additives (1–2%).

Molten paraffin wax and ferrofluid solution are vortexed for 3 s above the melting temperature of the paraffin wax. After heating the plastic test chip or CD using a hot plate at 80 $^{\circ}\text{C}$, the molten ferrowax was placed into each inlet holes located on the top plate of the chip using a custom-designed wax dispensing machine as shown in Fig. S1C. The molten ferrowax is driven into the channels by capillary action and solidified as the CD cools down. The dispensing volume of the ferrowax was automatically controlled (see ESI).

The molten ferrowax is oily and has very low surface tension because its major component is the hydrocarbon based oil. Therefore, the molten ferrowax flows into the microchannels by capillary action as soon as it was introduced to the injection hole (Fig. S1Bi).

If an extremely large amount of ferrowax is dispensed, re-solidification of melt ferrowax could stick on the downstream walls and could block the channel. Otherwise, most of the excess molten ferrowax flows into the AVC and therefore, the valve is formed only at the microchannels between the injection hole and the AVC as shown in Fig. S1Bii. In addition, by varying the exact location in which the ferrowax is placed, one can control the length of the valve as shown in Fig. S1Biii. The lengths between the injection hole and the chamber were usually smaller than 1 mm and therefore the volume of the LIFM was less than 100 nL (usually 20–40 nL).

In order to make NO-LIFM, the chip is cooled down to the room temperature and then the desired volume of molten ferrowax was injected into the ferrowax chamber. The

ferrowax access holes were subsequently sealed using optical adhesive tapes (AB applied Biosystems Inc., CA, USA).

2.2 Measurement of the response time and maximum hold-up pressure

In order to measure the response time of the LIFM, a test chip shown in Fig. S1A was used. Green ink was introduced with a flow rate of 100 $\mu\text{L min}^{-1}$ using a syringe pump (Harvard PHD2000, USA). A pressure of 46 kPa was maintained using a pressure sensor (MPX 5500DP, Freescale semiconductor Inc., AZ, USA) and a data acquisition system (34970, Agilent, CA, USA). At the same time, the laser beam (808 nm, 1.5 W) was irradiated at the valve and the total process was captured by using a high speed camera (Fastcam-1024, Photron, CA, USA). The response time was measured by analyzing the captured images.

The hold-up pressure of LIFM was measured again by using the pressure sensor (MPX 5500DP, Freescale semiconductor Inc., AZ, USA) and the data acquisition system (34970, Agilent, CA, USA) by flowing a dye solution with a flow rate of 100 $\mu\text{L min}^{-1}$ using a syringe pump (Harvard PHD2000, USA).

2.3 Operation of multiple LIFM on centrifugal microfluidic devices

In order to test the utility of the LIFM for lab-on-a-chip applications, it was implemented in a centrifugal microfluidic device. As shown in Fig. S2, a polar coordinate was used for the control of the ferrowax valves on a CD (see ESI). For example, in order to open the valve positioned at (r, θ) with respect to the laser home position $(r_0, 0)$, the disk is rotated with an angle of θ and the laser diode is moved with the distance of $r-r_0$ from the laser home to the center of the disk. For example, in order to transfer 100 μL of solution in reservoir A to reservoir B, as soon as the ferrowax valve is melted by laser irradiation for 1 s, the CD is spinning up to 30 Hz (revolution s^{-1}) with an acceleration of 30 Hz s^{-1} . These basic valve operation steps are repeated many times to control multiple valves on the CD.

2.4 Instrumentation

An experimental set-up for the centrifugal microfluidic control equipped with a disk spin unit, vision system, and laser motion control module was designed. A servo motor (SGMAS-01A, Yaskawa, Japan) and servo drive (SGDS-01, Yaskawa, Japan) are used for the precise positioning of the disk and to run various spin programs.

In order to obtain color images of the region of the interest on a rotating CD in real time, a strobe light (Hanra precision ENG, Korea), CCD camera (IK-TF5, Toshiba, Japan), and a retro-reflective fiber optic sensor (E3X-NA1F, Omron, Japan) were employed. A metal tape (2 mm $\times$ 2 mm) is placed on a CD and aligned with the light spot emitted from the fiber optic sensor. Therefore, whenever the metal tape comes over the fiber optic sensor, a pulse is sent to the image capture board and used as a trigger source for the camera and strobe light to grab one image frame per each rotation.

As shown in Fig. 1D, A stepping motor (PK-245-01A, Oriental, Japan), laser module guide (EK6, EF6, THK, Japan) and position sensor (EE-sx672) were employed for the precise positioning of the laser diode. A high power laser diode (L8828-72, Hamamatsu Photonics, Japan) was integrated with a Peltier cooler (VS1M-1.0-017-3.5, Vortex semicon, Korea) and copper plate for heat sink.

3. Results and discussion

3.1 Characterization of LIFM

The key concept of the proposed microvalve operation mechanism is to use metal nanoparticles as nanoheaters and heat by laser irradiation in order to obtain simple and rapid melting of multiple paraffin wax-based valves. However, when we first tried to mix magnetic particles with paraffin wax, we observed that the wax did not mix with most of the commercially available magnetic beads due to the hydrophobicity of the paraffin wax. However, the ferrofluid was well mixed with paraffin wax possibly because its major component is the hydrocarbon based carrier oil.

In order to test the efficiency of the melting process by the nanoheaters, laser beam (808 nm, 1.5 W) was illuminated on 1 mg of ferrowax located on the slide glass, the block of ferrowax was completely melted after 0.620 sec. On contrast, the pure paraffin wax did not melt at all even after 3 minutes (data not shown). Because the laser beam (808 nm) is not absorbed by water molecules, the laser irradiation only heats the nanoparticles but does not heat the water or biological reagents in the chamber.

In order to investigate the biocompatibility issue, real time PCR with the test samples (HBV (Hepatitis B virus) DNA solution, 10^6 copy mL^{-1}) which have been contacted with the ferrowax microvalves, have been compared with the control samples. The C_p value of the test sample (28.64 ± 1.6 , $n = 10$) was not different from the control sample (28.43 ± 0.45 , $n = 10$). Furthermore, the real-time PCR with the sample mixed with ferrofluids (1 : 1 volume ratio) showed no adverse effect on the PCR efficiency. C_p is defined as the cycle number at which the fluorescence passes the fixed threshold. It has been reported that 10-fold differences in the template DNA concentration results in 3.32 cycle differences in C_p when PCR efficiency is 100%.^{29,30}

The LIFM showed no negative effect in terms of bio compatibility within the experimental range. So far, the volume of ferrowax (less than 100 nL, usually 20–40 nL) is very small compared to 100 μL of the reaction volume. In addition, the contact time of the reagents with the ferrowax is almost negligible because the molten ferrowax is solidified instantaneously when the liquid is pumped to other chambers by centrifugation. If the reaction volume decreased to nano-scale, further investigation would be required to address the biocompatibility issues of both ferrowax and the plastic substrates.

The NC-LIFM was highly resistant to the pressure and no leakage was observed at a hydrodynamic pressure up to 403.0 ± 7.6 kPa. This is a significant value compared to other types of microvalves; e.g. hydrogel-based valves (390 kPa),³¹

paraffin-based valves (275 kPa),^{16,32} pinch valves (207 kPa),^{33,34} and ferrofluid valves (12 kPa).²⁵

Furthermore, long-term stability tests of the LIFM are under progress. For example, leakage tests were done by using the chips with preloaded ferrowax, kept at -4 °C, -20 °C, and room temperature (~ 25 °C) for two months. The maximum hold-up pressure was larger than 400 kPa for all of the test chips as shown in Fig. S3 (see ESI).

The mechanism of the melting paraffin wax with embedded iron oxide nanoparticles seems similar to previous studies such as melting polymer or ice matrix with embedded Au nanoparticles^{24–35} and also our previous report regarding cell lysis using magnetic particles and laser irradiation.²⁰ Strong absorption of laser light in metal nanoparticles generates heat and lets nearby wax matrix melt rapidly. Therefore, the melting time could be much shorter in the case of using nanoheaters compared to that of pure paraffin wax.

The response time to open the NC-LIFM and to close the NO-LIFM was only 12 ± 1 ms and less than 444 ms as shown in Fig. 2A and B, respectively. Compared to the response time of 210 s for the case of a conventional wax valve, it is a significant improvement that both NO-LIFM and NC-LIFM could be operated within 0.5 s without the need of additional chip space or extra tools such as an air pocket or external pump.

When we varied the composition of the ferrowax, the response time to open the valve was dramatically decreased as the volume fraction of ferrofluid increased as shown in Fig. 3A. The laser output power was fixed at 1.5 W and the response time was measured by analyzing images captured by high speed camera. The volume fraction of ferrofluid at 50% showed the shortest response time. Above 70%, the response time was short but the maximum hold-up pressure was decreased to 125 kPa. Therefore, 50% of ferrofluid was selected as the optimum condition at a laser power of 1.5 W.

Next, when we checked the effect of laser output power on the response time, dramatic decrease of the response time was observed as the laser output power was increased as shown in Fig. 3B. Above 1.5 W of laser power, the response time reached the minimum and does not decrease further. We selected 1.5 W of laser output power to build a portable device with minimum consumption of electric power and to use a small laser diode in order to reduce the size of the portable device.

3.3 Multiple LIFM operation on a rotating disc

In order to evaluate the performance of multiple LIFM, we have designed a microfluidic device using a centrifugal pumping mechanism. To test valving, metering, and mixing functions using the LIFM, a test CD was designed as shown in Fig. 4.

As shown in Fig. 4, the CD has 7 chambers and seven LIFM. Table S1 shows the spin program and the detail description of the process at each operation step (see ESI). The volume of the mixing chamber (chamber 4) was 250 μL and other chambers were 70 μL . 50 μL of 0.1 N NaOH solution were introduced to chamber 1 and chamber 3. 50 μL of 0.1 N HCl solution were placed in chamber 2. For the visualization,

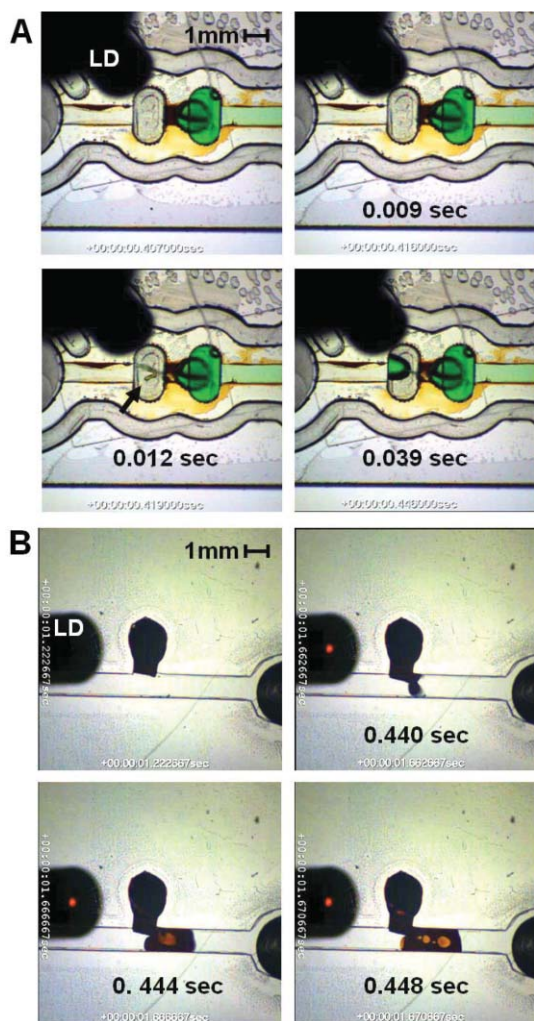


Fig. 2 Photo images of LIFM measured by high speed camera. (A) Upon laser irradiation (808 nm, 1.5 W), the ferrowax plug was melted at 12 ms and the channel was open to liquid flow (arrow in picture at 12 ms) when a pressure of 46 kPa was maintained. (B) Ferrowax in the NO-LIFM chamber burst into the main channel and complete sealing was obtained within 444 ms of laser irradiation. The volume fraction of the ferrofluid was 50%.

we used BTB (bromothymol blue) solution. BTB has a transition range of pH 6.0–7.6 and is yellow under acidic conditions and blue under basic conditions.

Only LIFM 7 was the NO-LIFM and the others were NC-LIFM. In order to flow a metered amount of liquid (50 μL) to the next chamber, we adjusted the position of outlet valves (LIFM 3 and LIFM 6) so that the left-over volume in the mixing chamber was always 50 μL .

Fig. 4B shows the initial state of the test CD, in which 50 μL of blue solution (chamber 1 and 3) and 50 μL of yellow solution (chamber 2) are contained in the input reservoirs and blocked by NC-LIFM under each chamber. At first, NC-LIFM 1 is opened by laser irradiation and the blue solution in chamber 1 was transferred to chamber 4 by centrifugal pumping (Fig. 4C). To open the NC-LIFM, the CD was rotated and the laser unit moved to the valve position using the methods shown in section 2.3. In order to transfer

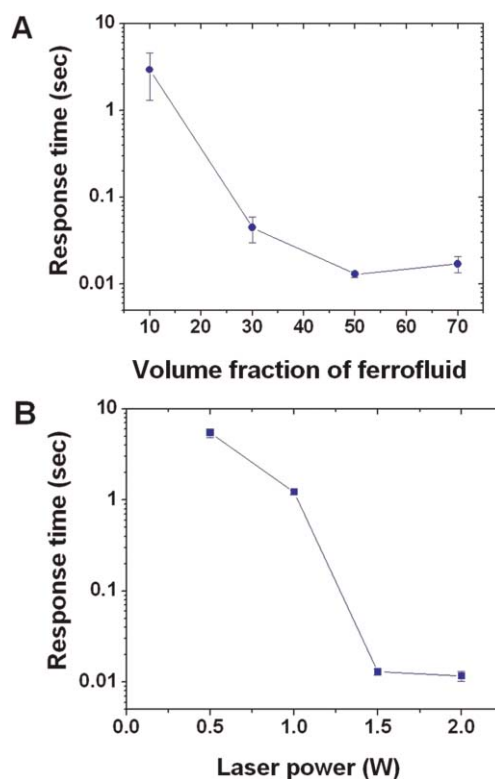


Fig. 3 Key factors for the response time of NC-LIFM. (A) Response time for the variation of mixing volume ratio with ferrofluid and paraffin wax. 50% mixing volume ratio is shown to be optimal value but the pure paraffin wax was not melted by 3 min of laser irradiation (data not shown). (B) Effects of the laser output power for NC-LIFM resulted in saturation at the laser output power of 1.5 W or more. The error bars are the standard deviation of 3 replicates. In Fig. 3B, the error bars are too small to be visible.

fluid, the CD was spun with an acceleration of 30 Hz s^{-1} and a maximum speed of 30 Hz (revolution s^{-1}) immediately after laser (1.5 W) irradiation on the NC-LIFM position for 1 s. Total operation time was 5 s.

Then, the yellow solution in chamber 2 is transferred to chamber 4 with the same manner as described above (Fig. 4D). In chamber 4, transferred blue and yellow solutions are mixed well by alternate spinning for 4 s three times (Fig. 4E). After mixing, the color changes to yellow by neutralization.

After opening NC-LIFM 3, the defined volume of 50 μL in chamber 4 is transferred into chamber 7 (Fig. 4F), and then NO-LIFM 4 blocks the microchannel between chamber 4 and chamber 7 by laser irradiation (Fig. 4G). To block the channel with NO-LIFM (LIFM7), no spinning step was necessary but laser irradiation was done for 2 s.

Next, the blue solution in chamber 3 is transferred into chamber 4 and mixed with residual solution (Fig. 4H), each defined volume of 50 μL of solution is transferred into chamber 5 and 6 respectively by opening NC-LIFM 6 and 7 (Fig. 4I and J).

Eventually, chambers 5, 6 and 7 have exactly the same volume of mixed solution with different compositions. The total process time was less than 1 min.

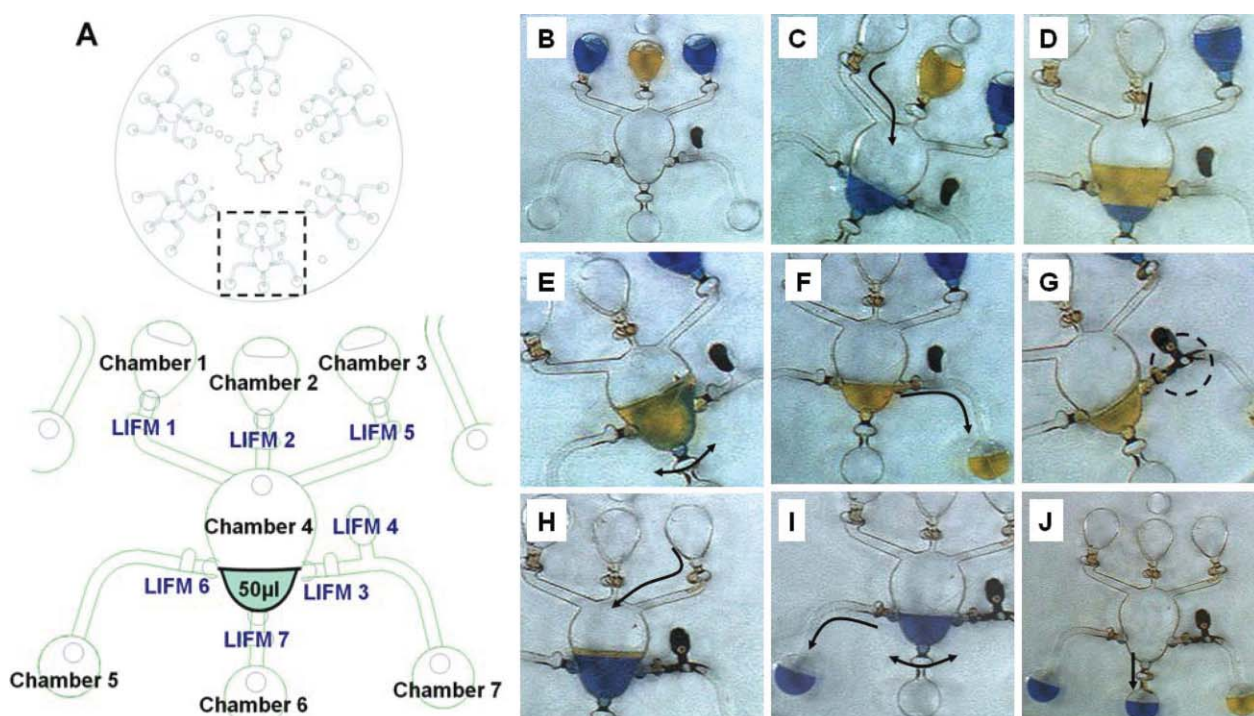


Fig. 4 (A) Schematic diagram of the microfluidic layout on a disc. (B–J) Photo images captured during the operation of the spin program.

The majority of centrifugal microfluidic platforms so far utilized either hydrophobic valves (hydrophobic surface prevents further liquid flow),³⁶ or capillary valves (liquid stops by a capillary pressure barrier at junctions where the channel diameter suddenly expands).^{37–39} The fabrication and simultaneous actuation of multiple valves were relatively simple. However, for the robust control of the valving operation, fine tuning of the spin speed as well as the local surface properties or dimensions of the microchannels were required. Furthermore, these valves can function only as opening valves; *i.e.* from the normally closed state to the open

state, not *vice versa*. As a result, only a limited number of biological assays that do not require complex fluidic design have been developed on a CD platform and launched on the market.^{36–43}

The proposed laser irradiated microvalves are not sensitive to spin speed or surface properties. Furthermore, it functions as both to open and to block the channel using the same actuation mechanism. As demonstrated in Fig. 4, various microfluidic functions such as metering, valving, and mixing were possible using the innovative LIFM together with centrifugal microfluidic pumping.

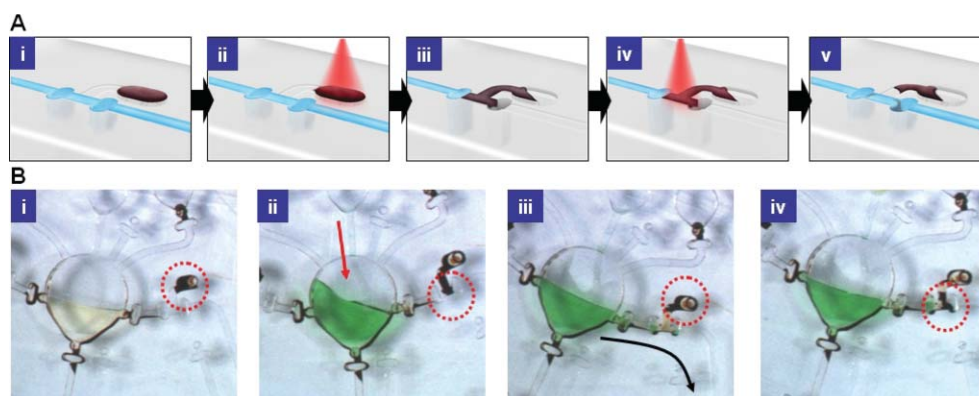


Fig. 5 (A) Schematic illustration of reversible operation of multifunctional LIFM. By adjusting the position of laser beam irradiation, the main channel could be opened or closed multiple times. (B) Single LIFM reversibly functions as both NC-LIFM and NO-LIFM. (i) 50 µL of yellow dye solution were transferred to the main mixing chamber. By laser irradiation on NO-LIFM chamber indicated by the dotted circle, the main channel is blocked as shown in (ii). (ii) The arrow indicates that 25 µL of green dye solution were transferred to the middle mixing chamber and mixed with yellow dye solution. (iii) As soon as the laser is irradiated on the ferrowax in the channel as indicated by the dotted circle in (ii), it is melted away and extra liquid, 25 µL of a mixture of green and yellow dye solution, located above the valve position is transferred to the waste chamber. In order to seal the channel again, the laser is again illuminated on the LIFM chamber as indicated by the circle in (iii). (iv) The main channel is blocked again and no liquid flows to the outlet waste chamber.

3.4 Design of multifunctional and reversible LIFM

Both designs of NC-LIFM and NO-LIFM shown in Fig. 1 are not reversible and each valve functions for only one purpose. However, multifunctional and reversible microvalves are also possible by simply changing the designs of the ferrowax loading chamber and the position of laser beam irradiation.

As shown in Fig. 5A, the microchannel can be closed by laser irradiation on the ferrowax chamber (i–iii) and then reopened by laser irradiation on the ferrowax valve in the microchannel (iv–v). The process can be repeated several times until the ferrowax is used up. This could be possible because of the local heating of microvalves by focused laser beam irradiation and low surface tension of the molten ferrowax.

A test CD was designed to demonstrate the operation of the reversible multifunctional microvalves. Fig. 5Bi shows that 50 μ L of yellow dye solution is in the main mixing chamber. In order to block the outlet channel, the laser was irradiated on the ferrowax chamber as indicated by a red circle. After 2 s of laser irradiation, the main channel was blocked as shown in Fig. 5Bii. The arrow indicated that 25 μ L of green dye solution was transferred to the middle mixing chamber and mixed with yellow dye solution.

As soon as the laser is irradiated on the ferrowax in the channel as indicated by a red circle as shown in Fig. 5Bii, it is melted away and extra liquid located above the valve position is transferred to the waste chamber as shown in Fig. 5Biii. In order to seal the channel again, the laser is again illuminated on the LIFM chamber as indicated by the red circle in Fig. 5Biii. The main channel is blocked again as shown in Fig. 5Biv.

4. Conclusion

A novel microvalve actuated by laser irradiation has been developed. The volume of the LIFM is less than 100 nL and the multiple microvalves could be operated by single laser diode (808 nm, 1.5 W). The microvalves are leak-free up to 403.0 ± 7.6 kPa and the response time to operate both normally closed and normally opened microvalves are less than 0.5 s. We also implemented the LIFM on centrifugal microfluidic platforms and demonstrated various microfluidic functions such as valving, metering, mixing, and distribution.

Because the LIFM is fast, small, biocompatible, simple to operate, and robust, it could be a key component for fully integrated lab-on-a-chip devices. Various biological assays such as pathogen DNA extraction from whole blood,²⁸ RNA preparation, molecular diagnostics of infectious diseases, genomic DNA preparation, various kinds of immunoassays, and blood chemistry analysis could be integrated on a CD platform using the novel LIFM.

Acknowledgements

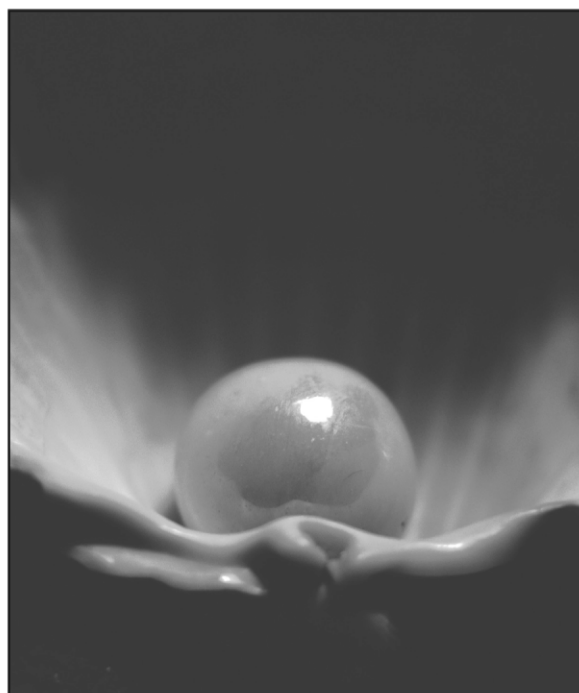
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