Hydrodynamic Focusing Micropump Module with PDMS/Nickel Particle Composite Diaphragms for Microfluidic Systems

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Summary

As part of the Post-Katrina project, a multi-fluidic speed-modulating (MFSM) micropump module combined with Tesla valves and hydrodynamic focusing micro-fluidic channels was designed, fabricated, and tested to help regulating sample flow across the nanowire-seeded sensor areas embedded in microfluidic channels. The size of the entire module is 33 mm x 25 mm x 8mm and comprises of three MFSM micropumps. The pumps are simultaneously operated by the same actuation source. Each micropump consists of Tesla-type valves in the bottom layer and PDMS/Ni-particle composite (PNPC) diaphragm in the middle layer. The deflection of the diaphragm is obtained by an external pneumatic force, and a permanent magnet controls the membrane displacement resulting from interaction of magnetic field and PNPC diaphragm. Analyses of the magnetic modulation force, flow rate of the MFSM micropump, and the hydrodynamic focusing were demonstrated.

Introduction

Microfluidic technology is dealing with fluids in micro-domain regarding volume, dimension, and power consumption. Since its first appearance it has enabled miniaturization, integration, and automation of assays to improve experimental throughput by utilizing small amounts of samples or reagents [1-3]. Microfluidic technology has been an integral part of an intensive research and development effort in nanotechnology during the last ten years [4]. Advanced technologies in biological micro-electro-mechanical system (BioMEMS) are supporting the trend to integrate nanometer scale materials and microstructures with microfluidics [4, 5].

Development in bio-medical and biosensor application technology has been advanced by converging microfluidics with nanotechnology such as nanowires, carbon nanotubes, and nanoparticles. Nanowires and nanostructures also have a great potential to provide point of care testing (POCT). For these applications precise detection and quantification of target diseases are critical. Nanowires and nanostructures can potentially increase the sensitivity and selectivity of the sensors [6]. Moreover, nanowire and nanostructure based sensors are label-free. These benefits from nanowires and nanostructures can significantly improve disease detection capability [7]. The combination of nanotechnology and microfluidics technologies needs addressing of research issues such as chip assembly, cost, accuracy, and integration at nano/micro/macroscale. The merging of nanotechnology with microfluidic enables promising biomedical applications such as drug delivery system (DDS), lab-on-a-chip (LOC) or micro total analysis system (μTAS), and POCT [8]. The hydrodynamic focusing module is a microfluidic assembly that allows fluid manipulation in small volumes with little effort with regard to fluid control and has the potential to be an add-on module to a modular biosensor chip [9-12].

Concept of hydrodynamic focusing module

The concept of the hydrodynamic focusing module is based on flow control using three reciprocating micropumps as illustrated in Fig. 1.

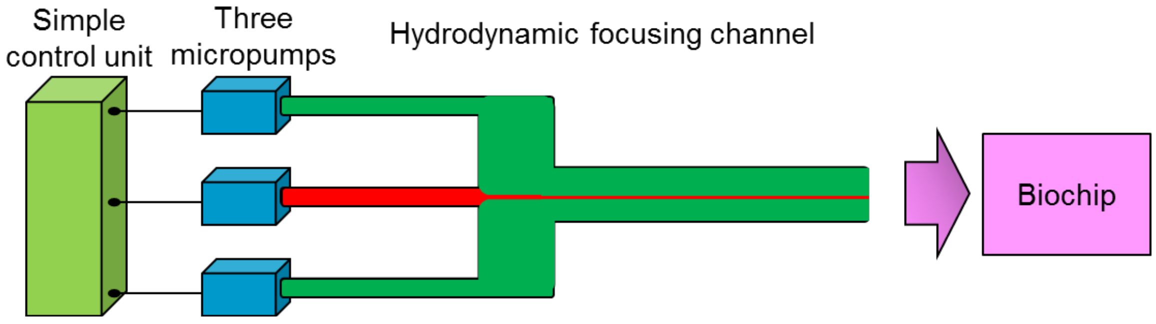

Fig. 1: Schematic of a hydrodynamic focusing module using customized micropumps.

Research efforts were primarily focused on building and qualifying the micropumps. Figure 2 shows the basic principle of operation of multi-fluidic speed-modulating (MFSM) micropump utilizing a flexible membrane (reciprocating micropump). The MFSM micropump is composed of a PDMS/nickel-particle composite (PNPC) diaphragm, actuator/modulator, valves, and chamber as shown in Fig. 2 (a). During micropump operation, the air pressure acts on the diaphragm to decrease and flatten periodically the chamber volume pushing fluid out of the chamber or drawing it into it (Fig. 2b). Flow control is realized via the valve-less nozzle and diffuser structures which are connected to the inlet and outlet of the chamber to rectify the flow [13]. The flow rate can be controlled by solenoid magnetic force acting upon the magnetic nanoparticles filled polymer diaphragm and changing the volume of the liquid pumped with each stroke (Fig. 2c).

The PNPC diaphragm is an important pump component allowing to controlling pump rate without changing the activating, external pneumatic pressure. Valves at either end of the pump body provide directional flow. In MFSM micropump, Tesla-type valves are realized because of their simplicity and relatively high performance. Combining a set of three pumps with a hydrodynamic focusing arrangement as illustrated in Fig. 1 and Fig. 2d results in a simple pumping unit (only one pneumatically driven air pulse is running all three pumps with constant frequency) that allows continuous manipulation of the central inlet channel.

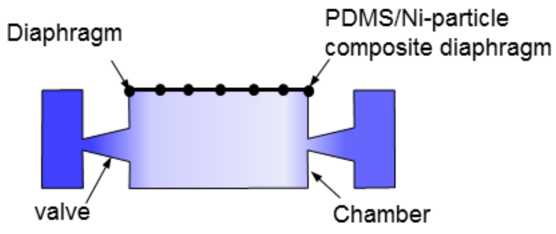

Fig. 2a:
Schematic of the fabricated micropump with no actuation.

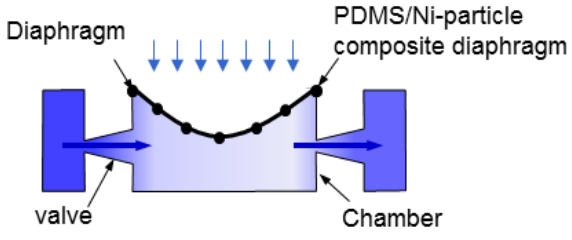

Fig. 2b:
Pulsed compressed air is periodically deflecting the diaphragm and pushing liquid out of the chamber with a net-flow determined by the Tesla-valve.

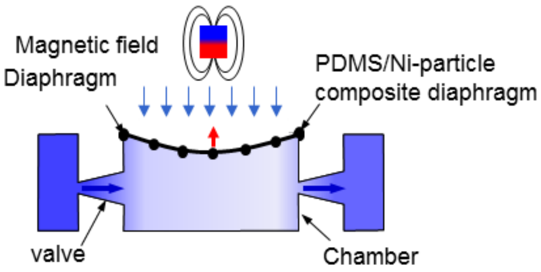

Fig. 2c:
Using an external magnet the deflection of the diaphragm is controlled and by this the amount of liquid pushed out.

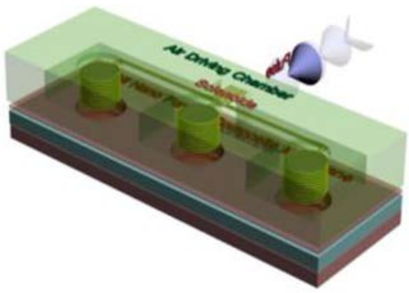

Fig. 2d:
An assembly of three pumps all actuated by one source and individually regulated by magnets allows flow manipulation in a hydrodynamic focusing unit.

Fabrication

A critical component of the pump is the filled PDMS membrane. For this Ni particles were thoroughly mixed into the PDMS raw material and casted and polymerized into ~100µm thick membranes. Payloads from 10-30% of Ni particles were successfully fabricated amd membranes were tested (Fig. 3). The membrane with 20% load is approx. 100 µm thick and behaves very much like a ~120 µm thick only PDMS membrane indicating that the added particles make the membrane stiffer. Measurements for 10% load show a more flexible membrane while a 30% particle load is only slightly stiffer than the 20%.This only marginal increase indicates non-uniform distribution of particles (agglomeration) affecting the membrane performance and effectively limits the payload to about 20%.

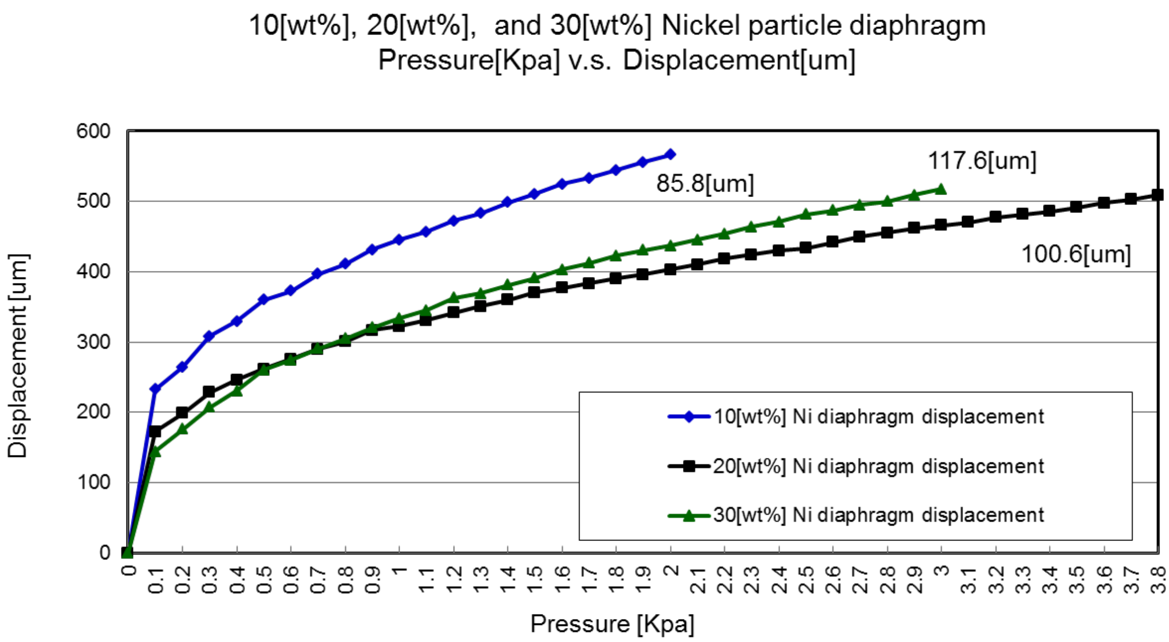

Fig. 3: PNC-diaphragm displacement measurement.

Figure 4 shows the actual design and some of the fabrication steps. More fabrication details are discussed in [9,14,15]. The pump body consists of molded PMMA housing structures replicated from a brass mold fabricated by precision micromachining. The PNPC membrane is attached to the pump housing and covered with a machined PMMA block which provides fluid interconnects (tubes), inlet for compressed air, and holes for permanent magnets interacting with the PNPC membrane.

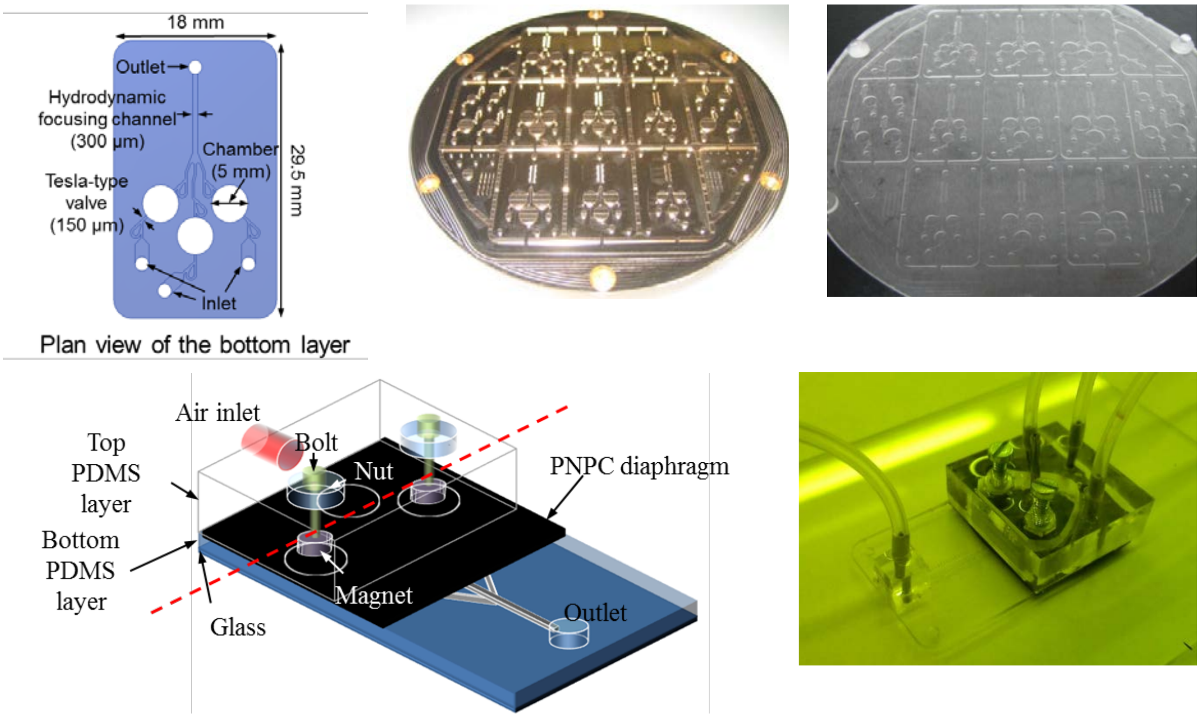

Fig. 4: Layout of one hydrodynamic focusing module (top, left), brass mold insert (top, middle) and replicated PMMA pump housings (top, right), along with schematic of assembled module (bottom, left) and actual device (bottom, right).

Module testing

Figures 5 display the schematic test setup for the MSM micropump module (left) along with a picture of the actual setup (right).

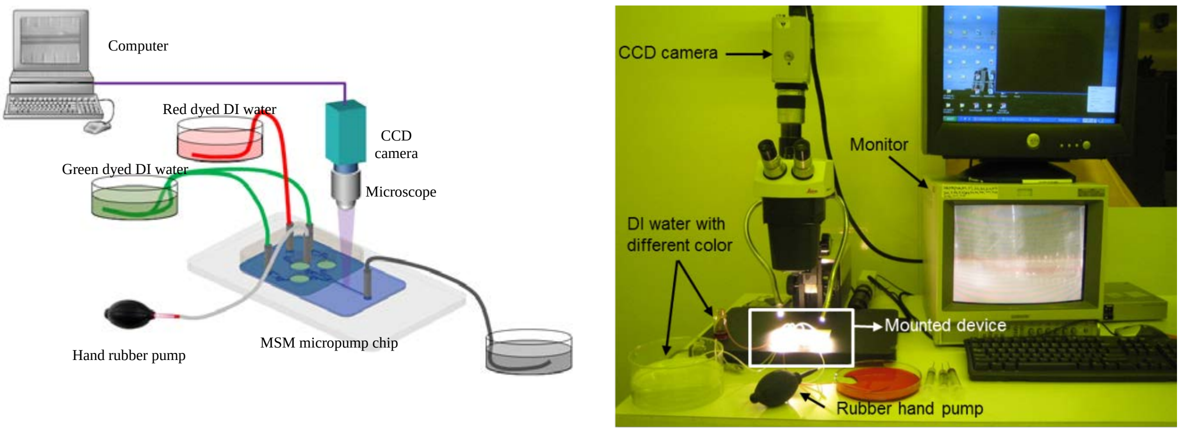

Fig. 5 left: schematic MSM micropump chip test setup; right: experimental setup using an optical microscope and a simple hand pump for actuation.

Two different colors of dyes are used for the test - red DI water for the central inlet and green for the two outer inlets. The device is placed under a stereoscope, and video pictures are recorded by a CCD camera.

Figures 6 illustrate the principle test setting. In Fig. 6 top all membranes are operated at maximum deflection achieving the highest flow rate frequency of $V_{flowrate}$ = 320 µl/min at a pump frequency of 2Hz. For an individual pump this calculates to a flow rate of approx. 107 µl/min, which is in good agreement with simulation results [9].

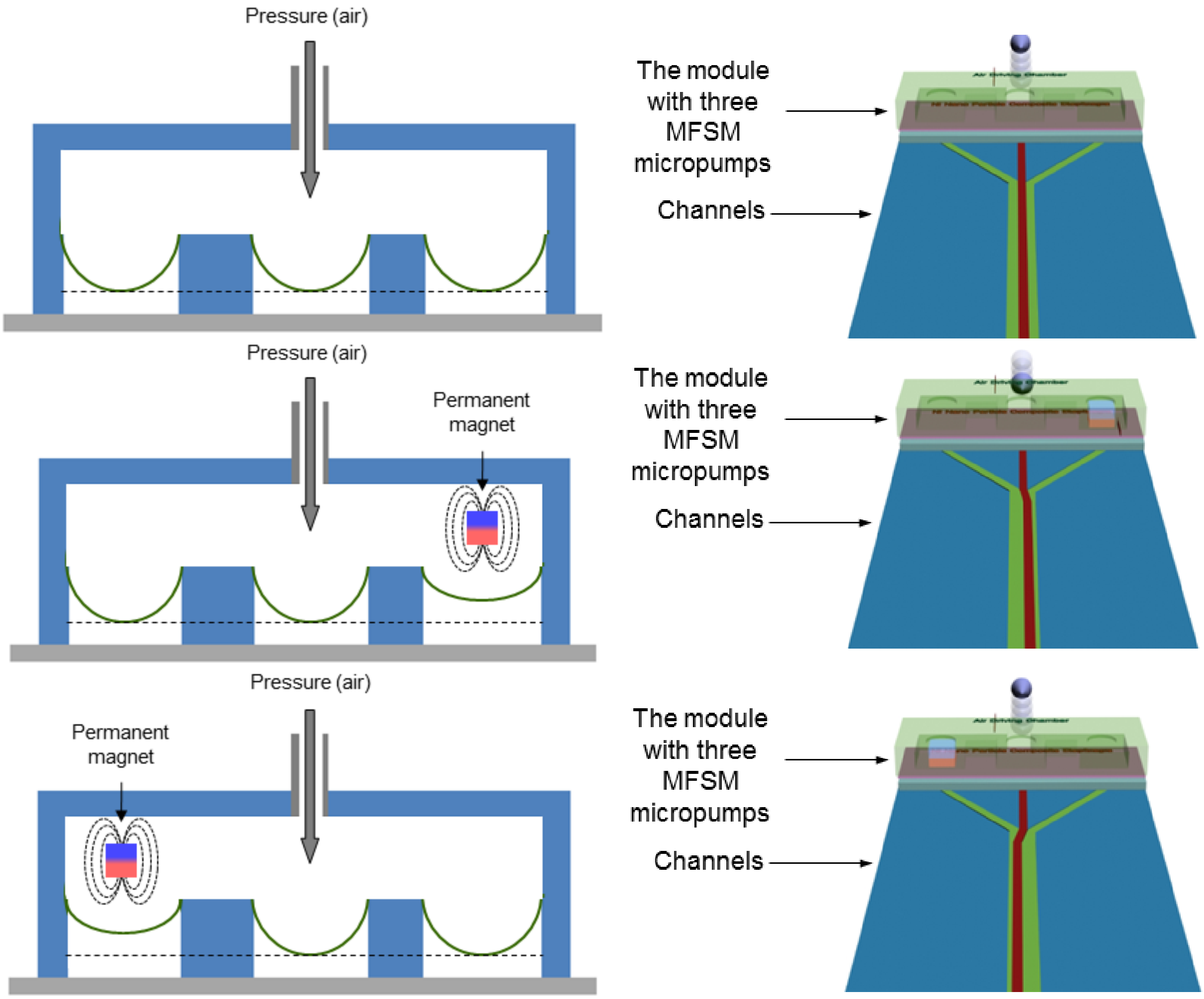

Fig 6: Placing of magnets on either of the outside chambers (left) leads to a modified volume of pumped liquid resulting in a shift of the center stream in the outlet (right). (Top) Center stream focusing with no modulation, (Middle) shift to the right when modifying the volume of the right pump, and (Bottom) same concept when manipulating the left pump.

The stream movement is modulated using a permanent magnet placed at different distances to the pump membranes of the left or right inlet, respectively as illustrated in the middle and bottom of Fig. 6. The movement range is from 2.1 mm to 0.375 mm on the right and from 2.1 mm to 0.5 mm on the left above the PNPC diaphragm achieved by a threaded bolt.

With reduced flow rate on either of the outer channels the central channel is shifting to the side with lower flow rate. Depending upon the magnet position (= magnetic field strengths exerting the diaphragm) the central stream is shifted to the right or left side and the widths of it is changing, too (Fig. 7). Manipulating the right pump flow rate the central stream is shifted to the right side in the outlet channel and its width is decreased from 120 µm to 22 µm when the magnet is moved from 2.1 mm to 0.375 mm (Fig. 7a). Similarly, for the left pump the stream width is reduced from 122 μm to 39 μm when moving the magnet from 2.1 mm to 0.5 mm (Fig. 7b). In Fig. 7c the results for the beam width at different magnet positions are summarized.

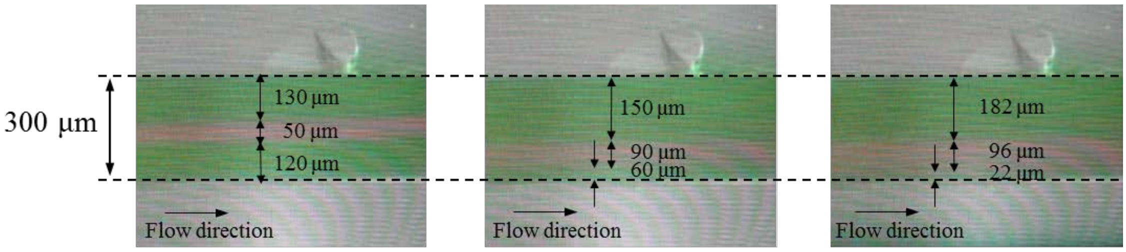

Fig. 6a: Modification of right micropump with external B field shifting the central stream to the right.

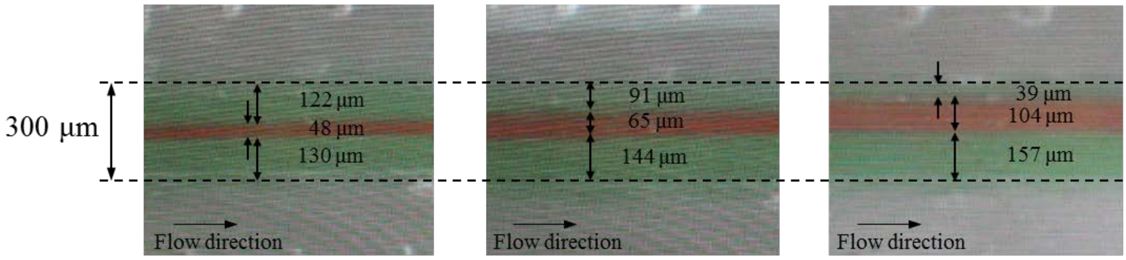

Fig. 6b: Modification of left micropump with external B field shifting the central stream to the left

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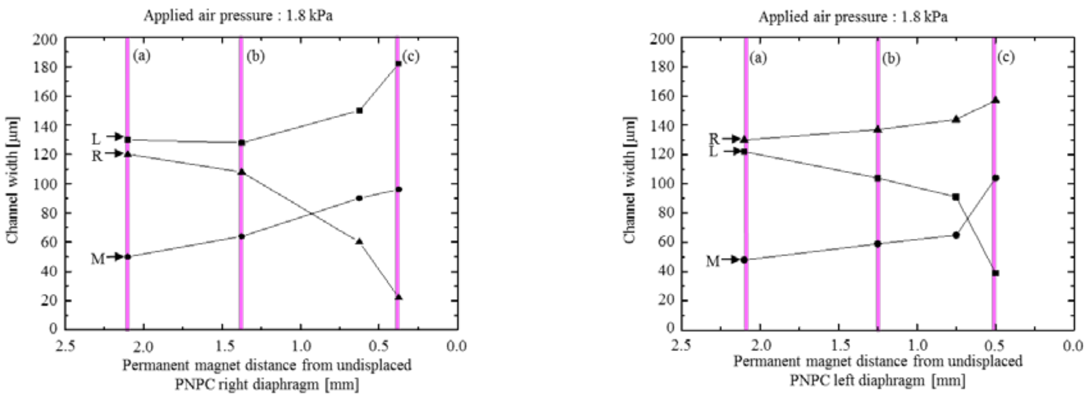

Fig. 6c: Measured focused stream width of shifted stream in right and left channel.

We have demonstrated precise fluid flow control using MFSM micropump module built from PNPC membranes and including a hydrodynamic focusing arrangement.

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