# Optothermorheological flow manipulation

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Optical methods for microfluidic flow manipulation offer a flexible, noncontact technique for both fluid actuation and valving. At present, however, such techniques are limited by their high laser power requirements, low achieved flow rates, or poor valve switching times. Here we demonstrate a microfluidic valving technique based on optothermorheological manipulation using a low-power 40 mW laser with switching times on the order of 1 s at high flow rates of 1 mm/s. In our approach a laser beam incident on an absorbing substrate is used to locally heat a thermorheological fluid flowing in a microfluidic channel. The resulting gelation in the heated region creates a reversible fluid valve. © 2009 Optical Society of America

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The ability to dynamically control and manipulate flow in microchannels is crucial to the development of viable lab-on-chip technologies. Various actuation methods based on electrokinetics [1] and pressure-driven flow [2] as well as flow valving techniques using pneumatic [2,3], ferrofluid [4,5], and polymer gel [6–8] based valves have been explored. A major issue with all these approaches is that the valving structures need to be designed, fabricated, and placed on the microchip *a priori*. As such, the microchannel network is essentially fixed, and on-the-fly flow reconfiguration is not possible. Fabrication methods are usually fairly complex (such as patterning multilayer soft-lithography systems or on-chip heaters), and there is need for extensive interfacing with the external environment (for example, with pneumatic lines or electrical connections). The issue of reconfigurability has been long addressed in electronic devices with field-programmable gate arrays [9] and even droplet microfluidic systems [10,11] but is largely unexplored in channel-based microfluidic systems.

Recent interest in optofluidics [12,13] has resulted in techniques using laser irradiation to manipulate fluids that could offer a solution [14–19]. For example, radiation pressure at the interface of two fluids has been used to deform the interface and produce microjets [14] of up to 100 $\mu$m length, though the power requirement for this was high (~1 W). Laser-induced heating has been used to drive the motion of droplets by thermocapillary actuation [16,17], although this is restricted to two-phase flow systems. Photothermal nanoparticles at a fluid–air interface have been used to drive flow by optical-to-hydrodynamic energy conversion [15] with flow rates on the order of ten to five hundred micrometers per second in 10–100-$\mu$m-wide channels. Recently, a laser scanning microscope has been used for fluidic actuation [18], where the repetitive motion of an IR laser results in heating and a subsequent viscosity change in water, driving flows with a velocity of 150 $\mu$m/s in channels of 10 $\mu$m height with a resolution of 2 $\mu$m. These optical manipulation techniques have advantages over more-traditional methods: being noncontact methods of actuation and flexible with minimum requirements for predefined geometries and allowing independent simultaneous actuation at multiple locations. At present, however, they are largely limited by the slow flow rates achieved (about a few hundred micrometers per second) and/or their high power requirements (~1 W).

One method to improve these results is through the use of light-actuated polymer gels [20–23]. Polymer gels that undergo light-induced phase change, either due to laser heating or a photoreaction in the gel, have been used to develop microfluidic valves. Although these techniques overcome some of the interfacing issues of pneumatic- and electronic-based valves, many of these techniques still require fixed, prefabricated geometries. To address this, Shirasaki *et al.* [21] have developed a technique that uses laser-induced IR heating to directly gel and rapidly valve a thermally responsive polymer solution in a 30-$\mu$m-wide, 5-$\mu$m-tall channel, though with high power requirements (~1 W). Sugiura *et al.* [23] have developed a technique that utilizes light irradiation of a photoresponsive hydrogel sheet to dynamically define channel geometries and valves on-the-fly that have a resolution of 10 $\mu$m. This robust and flexible fluid-manipulation method is, however, limited by the poor switching times of their structures (taking minutes to open and an hour to close).

In our work here, we present a rapid, low-power technique to carry out flexible fluid manipulation by light irradiation. This technique relies on the use of a thermorheological fluid that undergoes a reversible sol-gel transition on heating. A schematic describing our approach is shown in Fig. 1. Our chip consists of an upper part with a patterned microchannel bonded to a substrate with a coating that absorbs light at specific wavelengths. Thus when the absorbing substrate is selectively illuminated with laser light at these wavelengths, optical energy is converted to thermal energy to gel the thermorheological fluid flowing in the channel. A similar approach has been demonstrated by Boyd *et al.* [24], where the plasmon resonance of a metallic substrate was used to transfer optical energy to thermal energy. This optothermorheological method offers the flexibility to manipulate fluids without predefined valve geometries.

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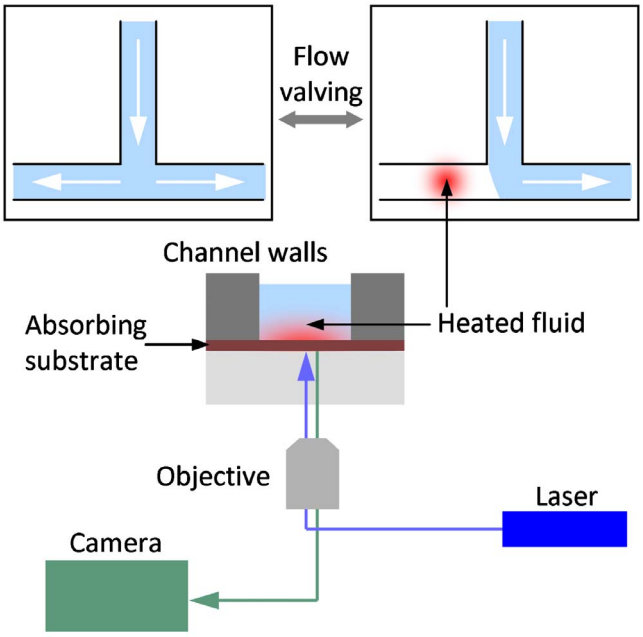


Fig. 1. (Color online) Schematic demonstrating valving technique with a laser and a microfluidic chip with an absorbing substrate.

We show switching times on the order of 1 s using a low-power 40 mW laser.

Optothermorheological valving is demonstrated here in a T-shaped microfluidic channel, as shown in Fig. 2(a) (Media 1). Initially, the flow rate through each of the bifurcating channels was the same. On illuminating one of the channels with laser light through a 20× objective (405 nm, 40 mW power, spot size ~10 $\mu$m), we were able to reduce and eventually stop the flow in this channel and redirect it to the other one. The same objective was used to image the sample, and flow was visualized using 1.5 $\mu$m silica particles (Duke Scientific). As shown in Fig. 2(b) (Media 1), when a nonabsorbing plain glass substrate was used, no such valving was observed. The thermorheological fluid used here is a 15% (w/w) aqueous solution of Pluronic F127 (BASF) with a gelation temperature of approximately 30°C [25]. The microfluidic channels were fabricated using standard soft lithography techniques with poly(dimethylsiloxane) (PDMS) (Ellsworth Adhesives). We used two different absorbing substrates: a plain glass substrate with gold sputter deposited on it (10–20 nm) and a cover slip coated with indium tin oxide (ITO) (120–160 nm, SPI Supplies) as well as a nonabsorbing plain glass substrate for control experiments. The absorbance of the sputtered gold substrate was measured to be 0.25 (transmission of 56%), of the ITO coated substrate was 0.34 (transmission of 46%), and of the plain glass substrate was 0.13 (transmission of 74%) at 405 nm, indicating that the ITO had the best absorption of the three substrates. Two channels width of 25 and 50 $\mu$m were used with the height constant at 25 $\mu$m. The results in Fig. 2(a) (Media 1) are for an ITO-coated substrate with a channel width of 50 $\mu$m.

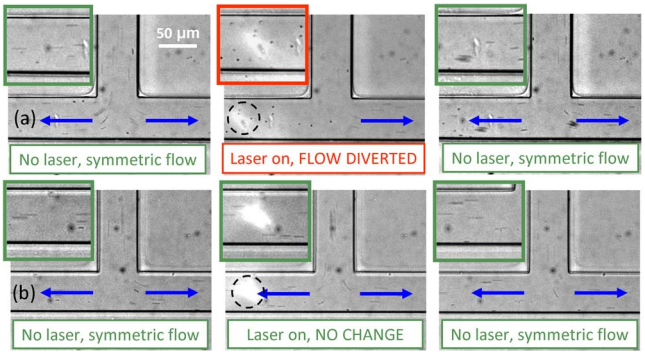


Fig. 2. (Color online) Demonstration of valving in a microfluidic channel (Media 1): (a) ITO-coated substrate (valving occurs), (b) plain glass substrate (no valving). Insets, a zoomed-up view of the flow in the valved channel; dashed circles, the position of the laser spot.

The results from characterization experiments are shown in Fig. 3. We varied the inlet flow velocity into a bifurcating channel and measured the final velocity in the valved channel after turning the laser on, as shown in Fig. 3(a). The control experiment here was with a glass substrate that showed no valving. The low Peclet number in our experiments (about 0.2) means that conductive heat transfer tends to dominate over convective or flow effects. Thus flow rate is not expected to affect the valving efficiency, resulting in the near-linear response of valved velocity to the inlet flow rate seen here. In general, we found that better valving was achieved for the wider channels. We also measured the time response, as shown in Fig. 3(b), and were able to turn the valve both on and off at timescales on the order of 1 s. The relaxation time for the formation and the dissociation of the gel itself is on the order of milliseconds [26]; thus the time required for heat transfer is the important time scale here. The flow measurements were carried out by analyzing the paths of the silica beads in the pluronic solution using ImageJ.

Finally, *in situ* temperature measurements using Rhodamine B [27] were also carried out, as shown in Fig. 4. We used Y-shaped channels here instead of T-shaped channels owing to experimental conve-

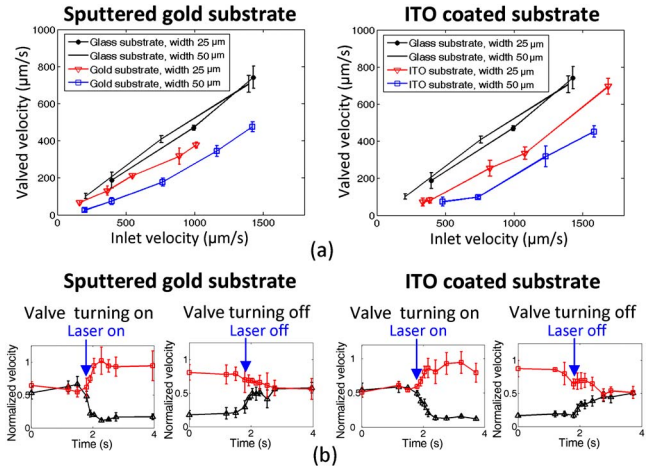


Fig. 3. (Color online) Flow measurements in channel. (a) Valved flow velocity as a function of inlet velocity for sputtered gold- and ITO-coated substrates. (b) Time response of valving for sputtered gold- and ITO-coated substrates (triangles, valved channels; squares, other channels). The results shown here are for 50-$\mu$m-wide channels.

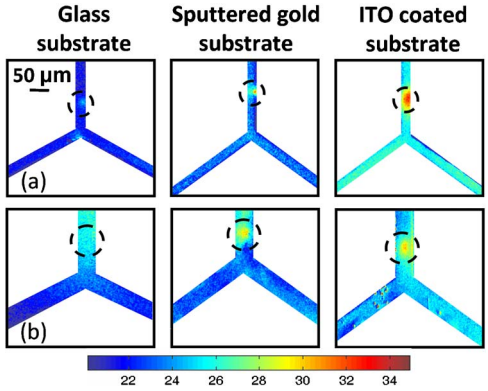


Fig. 4. (Color online) Temperature measurements: (a) channel width of 25 $\mu$m, (b) channel width of 50 $\mu$m. The region of heating by the laser is indicated by black dashed circles.

nience at the time, although this makes little difference at these low Reynolds numbers, where the effect of bend angle on pressure drop (head loss) is negligible. These results do show channel temperatures on the order of the sol-gel transition temperature; however, as was seen in Fig. 3(a), flow in the valved channel was not completely stopped. We expect that this is because the yield stress of the gel in the channel is not sufficient to withstand the applied pressure. We attempted to improve valving by increasing the beam power and also by changing the beam waist by using different magnification objectives. This resulted in either too much heating and bubble formation owing to evaporation or too little heating and no subsequent gelation. These temperature measurements also show that the ITO-coated substrate had slightly higher temperatures over a wider region of the channel compared with the gold-coated substrate, as expected. The 25 $\mu$m channel with the ITO-coated substrate had a higher temperature compared with the corresponding 50 $\mu$m channel, which is due to the lower thermal conductivity of the PDMS sidewalls ($\sim$0.18 W/mK) compared with the aqueous pluronic solution in the channel ($\sim$0.6 W/mK) [27].

Here we have shown the use of an optothermorheological technique to carry out valving in a microfluidic channel. We used a low-power 40 mW laser and obtained valve-switching times on the order of 1 s. Such a technique could be extended from simple valving to reconfiguring entire channel geometries by illuminating larger regions of the chip either using a mask or a digital micromirror display.

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