LOW-COST MICROFLUIDIC SINGLE-USE VALVES AND ON-BOARD REAGENT STORAGE USING LASER-PRINTER TECHNOLOGY

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ABSTRACT

We report for the first time the laser-printer-based fabrication of vapor- and pressure-resistant microfluidic single-use valves and their implementation on a centrifugal microfluidic "lab-on-a-disc platform". As an extension of this technology, we implemented long-term storage of liquids for up to one month with no signs of evaporation. This simple technology is compatible with a range of polymer microfabrication technologies and should facilitate the design and fabrication of fully integrated and automated lab-on-a-chip cartridges that require pressure-resistant valves or long-term reagent storage.

INTRODUCTION

Point-of-care (POC) diagnostic devices will revolutionize and improve global public health by diagnosing diseases in a timely manner, preventing epidemics, controlling chronic health conditions, tailoring treatments, and decreasing national health system costs. POC systems for deprived-resource settings require portability, disposability, low-cost, simplicity of use, ruggedness, and temperature independence [1-3]. They also need to deliver assay results with similar sensitivity, reproducibility, and selectivity to centralized laboratory tests [1-3]. Finally, POC devices should operate with minimal, non-expert operator attention.

Of the different technologies that currently exist to address this issue, microfluidic and lab-on-a-chip technologies have the potential and the toolset to make POC diagnostic systems a reality [3-4]. The lab-on-a-chip vision is to miniaturize clinical laboratory processes, integrating them onto disposable units the size of a credit card using minute amounts of complex samples and precious reagents. These autonomous and integrated chips would consist of different modules or components that would handle a complex sample such as blood, preparing it and mixing it with the necessary reagents to produce a signal that can be read by a miniaturized, even an on-chip, detection system.

Although the field of microfluidics has produced several components that in theory can help to realize this vision, the complexities of integrating and fabricating them at low cost are many and the challenges are daunting. We address one key component of this challenge by introducing a technology for the low-cost production of valves that can, among other tasks, enable on-chip long-term wet reagent storage.

Microfluidic valves and pumps are ubiquitous in integrated microfluidic systems, but fluid actuation and control can greatly add to the fabrication costs of integrated microsystems: external actuators may be needed to drive them [5] or their implementation into manufacturing processes may be a costly engineering challenge. Therefore, pumping and valving control for POCT should be easy to integrate into the manufacturing processes at minimum cost while still offering maximum flexibility in design and miniaturization of diagnostic integrated systems.

On-chip long-term reagent storage will be necessary for market success of many microfluidic point-of-care devices. Although both wet and dry reagent storage in microfluidic compartments has been reported [6-8] a key issue remains: delivering the reagents after an extended storage time, in a well-controlled fashion. Linder and colleagues demonstrated storage of reagents inside plastic tubing in liquid plugs separated by air gaps [8], but this and other methods that do not provide a sealed physical barrier are ill-suited to storage beyond a few hours due to migration of water in the vapor phase. Furthermore, this approach will not necessarily work in more complex, integrated microfluidic systems; alternatives are needed.

We report and demonstrate the fabrication of a single-use valve based on laser printing technology. The valves are 'opened' with a single laser shot or pulse. As an application of the same technology, we also demonstrate a system for the storage of liquid reagents in sealed reservoirs for up to 30 days with no significant evaporation. This simple technology is compatible with polymers and fabrication techniques such as hot embossing and multilayer plastic lamination.

Compared to other technologies [9], our approach requires lower laser powers and uses transparent foils (enabling addressing of valves on multiple fluidic levels). The electronics and software-control algorithms to operate the valves are simpler and the precision of positioning the laser spot less demanding since a general raster of the laser beam in the vicinity of the valve opens it.

DESIGN AND FABRICATION

Design

The schematic of the microfluidic single-use valves is shown in Figure 1. The device consists of three layers. The top layer features the main microfluidic channel, which connects to other microfluidic modules. Its continuity is interrupted at places where valves are necessary. The bottom layer contains a connecting microfluidic channel that links the segments of the top microfluidic channel. A plastic foil with laser-printed dots is sandwiched between these two layers. Two dots are aligned at the intersections of the top and bottom channels (Figure 1).

The purpose of each laser-printed dot is to absorb optical energy from the laser diode, rapidly heating and thus perforating the plastic foil by melting it, while clear areas of the foil remain unaffected. This reduces the required accuracy of aiming the laser, provided it is scanned over an area that encompasses the valve spot.

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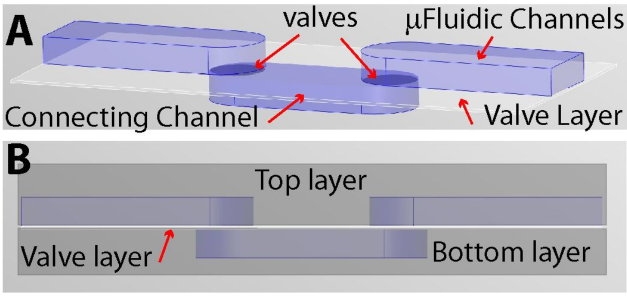

Figure 1: Schematic representation of the single-use valves. Upper microfluidic channels are connected through the bottom connecting channel (A). Between the two microfluidic channel layers is a thin film with laser-printed spots that define the valves as shown in the cross sectional view (B).

Operation of the valves is illustrated in Figure 2. Liquid flows into the upper left microfluidic channel. A laser diode is positioned to point at the first valve; a short pulse of light melts the plastic foil. The laser diode is then moved to the next dot and the operation repeated. Liquid then can be moved through the bottom channel into the upper right channel.

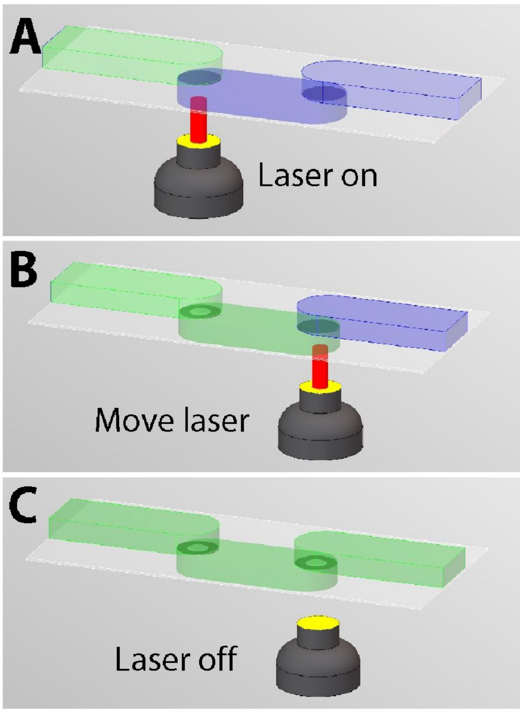

Figure 2: Operation of the single-use valves. Liquid (green) is loaded into the upper left channel (A). The laser diode is activated, sending a short pulse of light and melting the plastic (A), connecting the two channels. The laser diode is then moved to the next valve and the operation repeated (B, C).

The need for two dots per valve may not be obvious: one of the two could be perforated before assembly, reducing the complexities of positioning and control of the laser, but adding an additional step to the fabrication process. Pre-perforation of one dot would also eliminate the redundancy against leakage or slow permeation of water vapor afforded by two dots/valve. This trade-off is being explored and assessed.

A design for long-term reagent storage reservoirs for microfluidic devices, based on the functionality of the laser valves, is demonstrated in Figure 3A-C. A reservoir is defined in the upper layer and can be designed to hold any fluid volume. The valve for this storage reservoir is laser-printed at its peripheral end and at the intersection with a microfluidic channel that connects it to the rest of the microfluidic system. The barrier properties of the foil to store liquid reagents are exploited.

The operation of the device is shown in Figure 3D-E. After assembly of the device, reagents are loaded into the reservoir and encapsulated using pressure-sensitive adhesive (PSA) film. This film seals tightly the storage reservoir and prevents evaporation. Liquid from the container can be cleanly released into the channel by centrifugal or capillary actuation.

Fabrication

Devices shown in Figures 5 and 6 were fabricated using multi-layer lamination. A CO_2 laser (Laser Micromachining LightDeck, Optec, Belgium) system was used to cut the various polymer layers. To laminate the plastic layers, a thermal roller laminator (Titan-110, GBC Films, USA) was used. A laser-printer (resolution: 600dpi, LaserJet 4050 Series, HP, USA) was used to print dots onto a transparency film.

Connecting channels were cut from an 80-µm thick layer of PSA (AR9808, Adhesives Research, Ireland) and laminated onto a 250-µm poly(methylmethacrylate), PMMA, support layer (GoodFellow, UK). The width of the connecting microfluidic channel was measured to be approximately 400 µm. This assembly of channels constituted the connecting layer in both devices.

The upper chambers shown in Figure 5 were laser-cut from a 250-µm PMMA sheet; those in Figure 6 were cut from a 1.2-mm-thick polycarbonate layer (GoodFellow, UK). These layers were then laminated onto the connecting layer. Finally, a layer of PSA with laser-cut holes that function as vents was laminated on top of the chambers.

EXPERIMENTAL SETUP

Individual devices were mounted in a disc. A brushless DC motor with an integrated optical encoder (Series 4490, Faulhaber, Switzerland) was used to rotate the disc. We used a laser diode with similar characteristics to those used in commercial DVD-RW players (wavelength: 650 nm, power: 150 mW, Wicked Lasers, USA).

RESULTS AND DISCUSSION

Figure 4 shows a laser-printed dot on a transparency film. A laser pulse melts the plastic in less than one second. The minimum size of the spot is determined by the resolution of the laser printer. We printed dots with diameters down to 150 µm.

It is important to note that the transparency film was passed through the printer three times to impregnate the film with a high density of carbon ink microparticles and increase absorption of light from the laser diode.

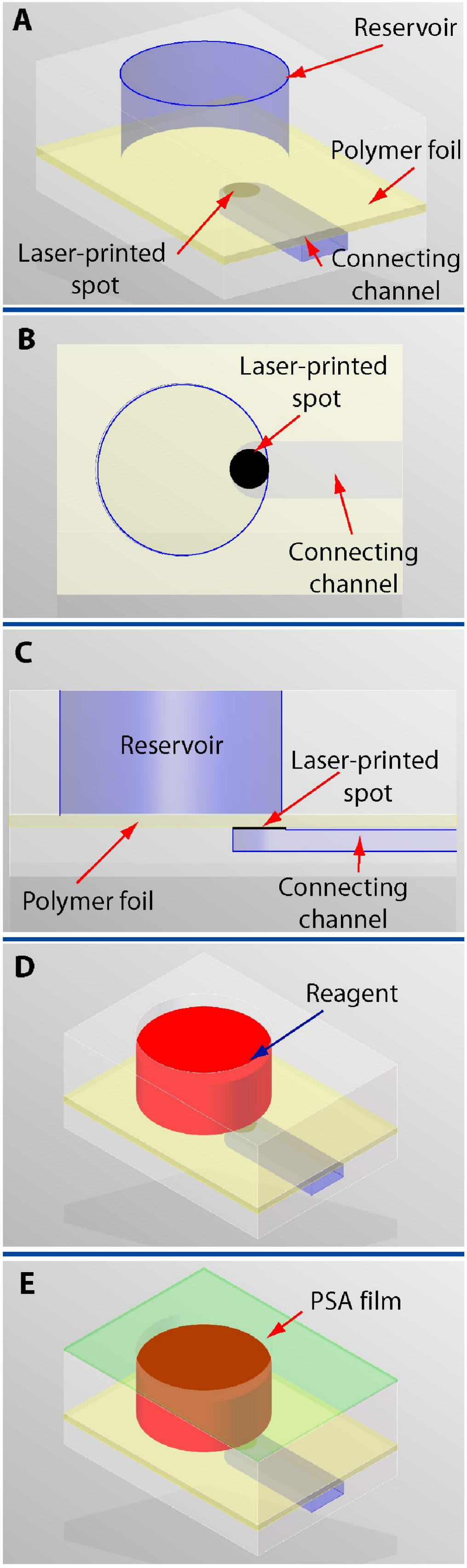

Figure 3: Illustration of on-board reagent storage using laser-printed valves. The polymer foil is placed between the microfluidic connecting channel and the reservoir. Cross sectional (B) and frontal (C) views are shown. Reagent is loaded in the reservoir (D) and covered by a pressure-sensitive adhesive film (E).

Experiments performed with foils printed in a single pass did not absorb enough energy to melt the plastic. An increase in the laser power would melt the plastic for a single-pass laser-printed film.

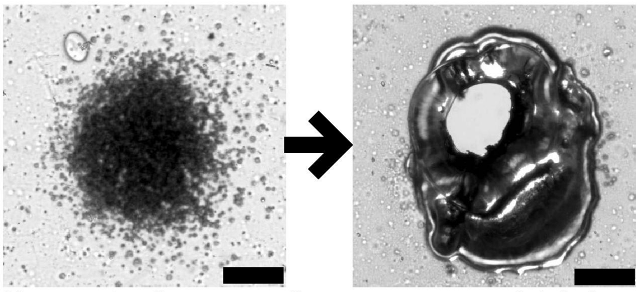

Figure 4: Laser-printed spot on a poly(ethylene terephthalate) (PET) substrate (left). A laser pulse melts the plastic foil (right) and creates a hole that allows communication between two channels. Scale bar: 400 μm.

To demonstrate the laser valve concept, we fabricated a centrifugal microfluidic "lab-on-a-disc" cartridge with two chambers connected by a microfluidic channel (Figure 5). The solution is initially loaded into the upper chamber. The disc was rotated at different speeds and no leakage was observed through the valve even while spinning at 5000 rpm. The disc was then stopped and light from the laser diode aimed at the laser-printed area, creating a communication port in less than 1 sec. The disc was spun again and the solution was fully transferred to the bottom chamber.

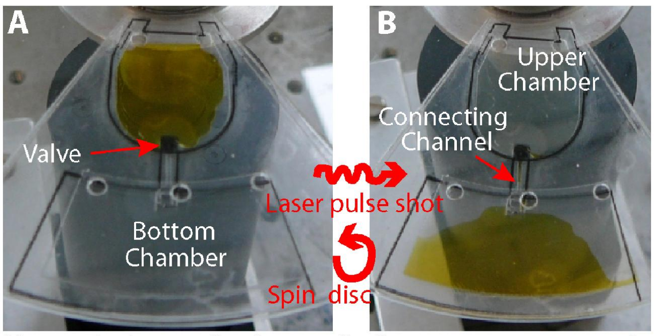

Figure 5: A centrifugal microfluidic system consisting of two chambers connected by a channel is shown. The valve is the laser-printed black dot (A). After the valve is melted, the disc is spun for a few seconds and all the liquid is transferred to the bottom chamber.

Figure 6 illustrates the system design for the on-board reagent-storage device. In this system, two reservoirs are defined near the center of the disc. Two solutions are loaded into the reservoirs and sealed with PSA-coated film. The valves are then opened and the disc spun to displace the liquid into a mixing chamber. Stored solutions did not evaporate for a period of 30 days, and suitable polymers could extend this significantly. The valves prevent fluid leakage at rotation rates of at least 5000 rpm (corresponding to 840x***g***).

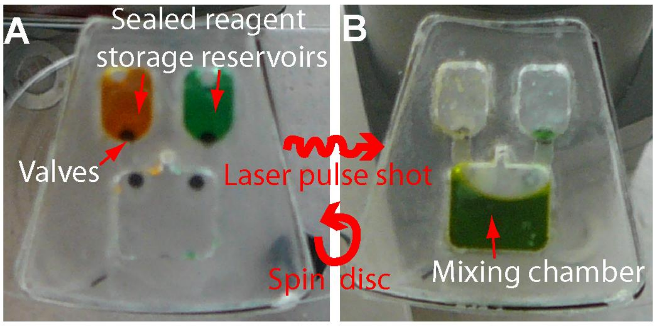

Figure 6: On-board storage of two solutions. Two solutions are initially loaded in two different compartments and sealed to prevent evaporation (A). After the laser valves are opened, the two solutions flow into the mixing chamber by spinning the disc (B).

CONCLUSIONS

A new laser-printed valve technology facilitates the design and fabrication of fully integrated and automated lab-on-a-chip cartridges that require pressure-resistant valves or long-term reagent storage. One key advantage is the absence of mechanical components in the valve and its actuation, facilitating its manufacture and use.

This technology can be adapted to multilevel microfluidics where layers of microfluidic channels are separated by valving layers. As long as the laser-printed spots do not overlap, the appropriate valve can be selected on demand and channels on different layers connected at will.

Future work will involve the full characterization of these laser valves. Melting temperatures, laser powers, and the effects of any (bio)chemically active residue of the melting process will be investigated.

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REFERENCES

[1] P. Yager, T. Edwards, E. Fu, K. Helton, K. Nelson, M.R. Tam, B.H. Weigl, "Microfluidic diagnostic technologies for global public health", *Nature*, vol. 442, pp. 412-418, 2006

[2] P. Yager, G.J Domingo, J. Gerdes, "Point-of-Care diagnostics for global health", *Annu. Rev. Biomed.Eng.*, vol. 10, pp. 107-144, 2008

[3] C.D Chin, V. Linder, S.K. Sia, "Lab-on-a-chip devices for global health: Past studies and future opportunities", *Lab Chip*, vol. 7, pp. 41-57, 2007

[4] G. Whitesides, "The origin and future of microfluidics", *Nature*, vol. 442, pp. 368-373, 2006

[5] Z. Hua, R. Pal, O. Srivannavit, M. A. Burns and E. Gulari, "A light writable microfluidic "flash memory": Optically addressed actuator array with latched operation for microfluidic applications", *Lab Chip*, vol. 8, pp. 488-491, 2008

[6] E. Garcia, J.R. Kirkham, A.V. Hatch, K.R. Hawkins, P. Yager, "Controlled microfluidic reconstitution of functional protein from an anhydrous storage depot", *Lab Chip*, vol. 4, pp. 78-82, 2004

[7] R. Seetharam, Y. Wada, S. Ramachandran, H. Hess, P. Satir, "Long-term storage of bionanodevices by freezing and lypholilization", *Lab Chip*, vol. 6, pp. 1239-1242, 2006

[8] V. Linder, S.K. Sia, G.M. Whitesides, "Reagent-loaded cartridges for valveless and automated fluid delivery in microfluidic devices", *Anal. Chem.*, vol. 77, pp. 64-71, 2005

[9] P. Zucchelli, B. Van de Vyver, "Devices and methods for programmable microscale manipulation of fluid", U.S. Patent 7,152,616 (2006)