



A versatile plug microvalve for microfluidic applications



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ABSTRACT

Most of the available microvalves include complicated fabrication steps and multiple materials. We present a microvalve which is inspired from macroplug valves. The plug microvalve is fabricated by boring a hole through a rigid cylindrical rod and inserting it through a microfluidic chip. It simply functions by rotating the rod which aligns or misaligns the valve port with the microchannel. The rod is made up of a rigid material for applying the valve to an elastic polydimethylsiloxane (PDMS) microchannel. The valve can also be used for a rigid channel by inserting the rod into an elastic tubing. Therefore, the presented microvalve can be used for both elastomeric and thermoplastic channels. The plug microvalve can be applied to a prefabricated microchannel and does not require modification of the mold design. We have verified the repeatability and robustness of the valve by repetitive operation cycles using a servo motor. The plug microvalve is adaptable to numerous microfluidic applications. We have shown three modes of operation for the microvalve including fluid flow control across multiple intersecting channels. Integrating the microvalve to some commonly used microfluidic designs, we demonstrated the versatility and the practicality of the microvalve for controlling flow focusing, microdroplet sorting and rapid chemical agent detection. This low-cost microvalve significantly minimizes the prototyping time for microfluidic systems.

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1. Introduction

Fully integrated microfluidic devices require several components such as channels, pumps, mixers and valves. Early years of the birth of microfluidics witnessed the development of these basic components using different methods. In the literature, a variety of microvalves have been reported which employ electro active polymer [1], piezoelectric materials [2], ferrofluids [3], electrostatic actuation [4] or phase change materials such as paraffin wax [5], hydrogel [6], or thermo sensitive materials [7]. There are also single-use burst valves that are normally-closed and opens irreversibly [8]. The passive capillary valves can also be considered as single-use since reactivation of the valve requires complete drying of the chip [9]. One can refer to review articles for numerous other types of microvalves [10,11]. Amongst these valves, the pneumatic membrane valve had a profound impact in the field [12]. The high scale integration of these valves allowed exquisite control of fluids in tiny compartments [13]. The multi-layer microfluidic system uses a control layer to adjust the pressure in order to activate or deactivate each valve. The similar doormat valves, which rely on SU-8 molds, operate in a similar way [14]. However, these

microvalves require precise multi-layer microfabrication and is not suitable for rapid fabrication. In order to address these challenges the simplistic twist valves have been developed [15]. These valves do not require any off-chip components and can be fabricated relatively easier compared to pneumatic membrane valves. They do not need any pressure or power to retain their state, thus they are applicable for portable applications. However, these twist valves still rely on deflection of a thin PDMS membrane, which is achieved either by twisting a screw or by actuation of a spring plunger [16]. Their fabrication is tedious and include several additional steps such as precise alignment, vertical integration of a screw and curing of a second material to form the threads. It is important to note that both pneumatic membrane valves and twist valves are pinch valves that function based on deflection of an elastic layer which requires microfabrication.

In recent years, microfluidic community has focused more on the application of integrated lab-on-a-chip (LOC) devices with increasing number of researchers from diverse backgrounds. Bringing in new opportunities and new research directions, the increasing demand for more capable systems poses some challenges such as the need for expertise in all the components of an integrated LOC system. It is interesting to note that although micropumps and micromixers are quite standardized and easy-to-reach for most researchers, microvalve is still a tricky component especially for people without microfabrication expertise. There is

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still not a gold standard microvalve available in the market. Therefore, there is a gap in the field for low-cost, versatile microvalves that can be fabricated and applied by non-experts.

In this study, we present arguably the simplest type of microvalve that can be exploited in microfluidic systems. We report a plug microvalve that is inspired from macroscale quarter turn ball valves. The plug microvalve is fabricated by boring a hole through a cylindrical rod which is inserted into a hole punched through the microchannel. This valve inherits all the benefits of the twist microvalve; (i) it does not require any change of the original channel design, (ii) it is very low-cost, (iii) it is truly integrated and operates without any off-chip components, (iv) it only requires power during state change. Unlike the twist valve, the plug microvalve can be fabricated in less than 5 min which requires no skillset other than punching and drilling holes. Additionally, the presented valve can be integrated to both elastomeric and thermoplastic microfluidic devices such as polydimethyl siloxane (PDMS), polymethyl methacrylate (PMMA), acrylonitrile butadiene styrene (ABS), polycarbonate (PC) and polystyrene (PS) which is a unique feature. Since it works by completely blocking the microchannel rather than pinching the channel, it works for any channel size or shape (rectangular or round microchannel).

2. Fabrication and characterization of the plug micro valve

The operation of the valve is shown in Fig. 1. As seen, the valve is composed of a rod which is inserted to a channel. The rod contains a hole that is aligned with the microchannel in its ON position. Herein, we used polylactic acid (PLA) rods owing to their mechanical properties. PLA is a commonly used biocompatible 3D printing material which is readily available. It has a Young's modulus of 3.5 GPa which provides the rigidity required during the operation of the valve and also ease of fabrication during hole opening.

2.1. Fabrication

The plug microvalve is fabricated in four simple steps. First, we cut a piece of rod from PLA filament stock and bore a hole through the radial axis of the rod (Fig. 2a). Then, we bend the tip of the rod 90° to the direction parallel to the hole using a hot air gun set at 200 °C (Fig. 2b). This allows ease-of-handling during manual operation. Then, a through hole is opened across the microfluidic chip intersecting the microchannel at the point where we need the valve (Fig. 2c). Finally, the rod is inserted into the hole on a flat surface so that the hole aligns with the microchannel (Fig. 2d).

The through hole of the rod is obtained using a benchtop micro miller (Proxxon MF 70) with tungsten carbide drill bits (Proxxon 28321). PLA rod is fixed into a V-shape groove along a metal fix-

ture (Fig. 2a). Drilling is done gradually by 4–5 rapid up and down motion of the drill bit in order not to increase the temperature of PLA and cause melting. In order to achieve the alignment of the hole with the microchannel in the final device, the distance from the center of the hole to the bottom of the rod should match the height of the microchannel from the bottom of the substrate. In this way, inserting the rod all the way into the microfluidic chip on a flat surface ensures the alignment. The horizontal alignment of the rod with the channel is achieved when punching the hole through the device which is performed under stereo microscope (Fig. 2c). Sample rods with 600 μm and 200 μm diameter holes are shown in Fig. 2a inset. The dead volumes for these microvalves are 0.48 μl and 0.053 μl , respectively, which are negligible for most applications.

The rods shown in Fig. 2a are used for soft PDMS microchannels. For microchannels made out of rigid materials such as PMMA, the rod should be elastic to obtain a successful sealing. This is achieved by inserting the PLA rod into a silicone tubing and performing the hole drilling step explained as above. A resultant valve can be seen in Fig. 3c, for which we used a silicone tubing of 0.8 mm ID and 2.4 mm OD. (Versilic spx-50). Fig. 3 shows the plug microvalves integrated to a PDMS (a–b) and a PMMA (c–d) microfluidic device. Fig. 3a and 3c show the OFF position of the valve at which the bent section of the rod is perpendicular to the microchannel. Fig. 3b and 3d show the ON position with the red dye solution filling the microchannels. PDMS channels are obtained using conventional soft lithography using SU-8 molds and sealed by bonding to a blank PDMS piece using oxygen plasma activation [17]. PMMA devices were obtained by CO₂ laser cutter (Epilog Zing) and sealed by a PMMA piece using double sided tape. After fabrication of the microfluidic devices, the location of the valves were marked using a marker pen. Then, holes are punched through the PDMS or PMMA device using punching or drilling, respectively. The larger the hole through the PLA rod, the more tolerant the system to misalignments.

2.2. Leakage test

We tested the sealing of the valve using a pressure pump system (ElveFlow OB1). We connected the inlets of the microchannels shown in Fig. 3 to a DI water supply and gradually increased the inlet pressure up to 2 bar. The valves with 200 μm and 600 μm hole diameters withstood the maximum pressure of our test setup (2 bar) for both the PDMS device and the PMMA device. During these tests, we have not observed any leakage around the valve thus the plug microvalves were successful in sealing around the hole. It should be noted that successful sealing of the plug microvalve depends on the geometrical parameters and also the chip/rod material elasticity. Although it is challenging to draw a universal

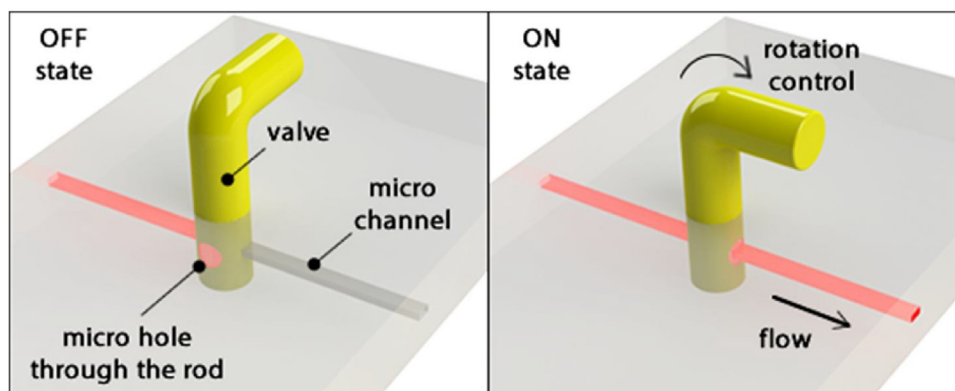


Fig. 1. 3D schematic drawing of the plug microvalve at (a) ON and (b) OFF position.

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