OPTOFLUIDIC, CONTACT-FREE 1x3 LIGHT-SWITCH FABRICATED ON A MONO-LAYER DEVICE

Emanuel Weber[1,2*], Franz Keplinger[1], Michael J. Vellekoop[2]
[1]Institute of Sensor and Actuator Systems, Vienna University of Technology,
Gusshausstrasse 27-29 / E366, 1040 Vienna, Austria
emanuel.weber@tuwien.ac.at, franz.keplinger@tuwien.ac.at
[2]Institute for Microsensors, -Actuators and -Systems, MCB, University of Bremen,
Otto-Hahn-Allee Gebäude NW 1, 28359 Bremen, Germany
mvellekoop@imsas.uni-bremen.de

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ABSTRACT

We present an on-chip 1x3 light switch exploiting an optofluidic principle. Compared to other works mechanically moving elements were entirely omitted, eliminating any wearing or sticking issues and nearly infinite switching sequences are possible. Furthermore, the consumption of solutions is kept at the very minimum since no permanent flow through the device is needed. The principle is based on total internal reflection at the solid-liquid interface of a liquid filled microfluidic channel. Depending on the refractive index of the solution light is either reflected and guided towards the first output or transmitted and routed to another position. Placing two channels after each other provides three possible optical outputs. Fluorescence images were taken to evaluate the operation of the device. In accordance with that, the optical signals were detected by photodetectors at all three outputs and verified the faultless switching characteristics. By integration of more than two channels the number of switching possibilities can further be increased. The devices were fabricated in PDMS enabling fast and cost-effective reproduction. For the master device fabrication a new rapid proto-typing technique applying dry resist lamination has been used. This principle is a promising approach to enhance the performance of devices implementing fluorescence analyses. Excitation light can be controlled in terms of place and exposure time allowing for an accurate and time limited activation of small sample volumes.

1. INTRODUCTION

Within the field of microfluidics optical principles are embedded in different ways for actuation as well as sensor elements. One example is fluorescent labeling which is exploited for the visualization and examination of various biological and chemical reactions. For this kind of analysis optics plays an important role in both excitation and detection. Taking into consideration the permanent pursuit for self-contained, miniaturized lab-on-a-chip devices, the integration of optical components on a microfluidic chip is the next obvious step. Active elements, such as coherent light sources [1], as well as passive ones, such as waveguides [2], have already been successfully implemented. Compared to its solid counterparts such optofluidic devices provide an enormously increased flexibility as well as tunability. Liquids can either be easily exchanged or streams of liquids in a microfluidic channel can be changed in size by alternating their inlet velocities resulting in continuously reconfigurable characteristics of the devices.

Especially for on-chip fluorescence excitation a sophisticated optical arrangement is crucial. The examined amount of sample in microfluidic devices is extremely low calling for a precise spatial control of possible stimuli (e.g., light for the excitation of fluorescence). Furthermore, a temporarily confined time slot for the exposure of

* Corresponding author

the analyte to light results in reduced photo bleaching issues. This has led to the investigation of various on-chip light modulation principles. Song *et al.* [3] published a 2x2 optical switch based on pneumatically opened and closed air gaps. Campbell *et al.* [4] have developed a multi-layer 2x2 optical switch exploiting the different reflection/transmission properties of two liquids. Both groups apply mechanically moving parts for the light switching process. Lamb *et al.* [5] proposed an optofluidic switch without any moving parts based on a liquid core/liquid cladding waveguide. In this work flow rates are adjusted carefully to alter the width of the liquid core resulting in two possible light switching states. Although providing good switching characteristics, the use of mechanically moving parts automatically induces wearing and sticking issues. The proposed principle based on a liquid core/liquid cladding waveguide does not employ any moving elements but depends on a permanent supply of fresh liquids at relatively stable flow rates.

In this paper we report on an optofluidic, contact-free 1x3 light switch avoiding those two disadvantages. This device takes advantage of the exchangeability of liquids in microfluidic devices. The exploited principle is illustrated in Fig. 1. Light guided towards a microfluidic channel in a relatively flat angle (illustrated by green lines) is either reflected or transmitted depending on the refractive indices (n) of the device material and the medium in the channel (blue rectangles in the figure). If the refractive index of the medium is sufficiently low (in relation to the index of the device material), incident light rays experience total internal reflection at the solid-liquid interface (Fig. 1a). On the other hand, filling the channel with a solution matching the refractive index of the chip material allows light to be fully transmitted through the channel (Fig. 1b).

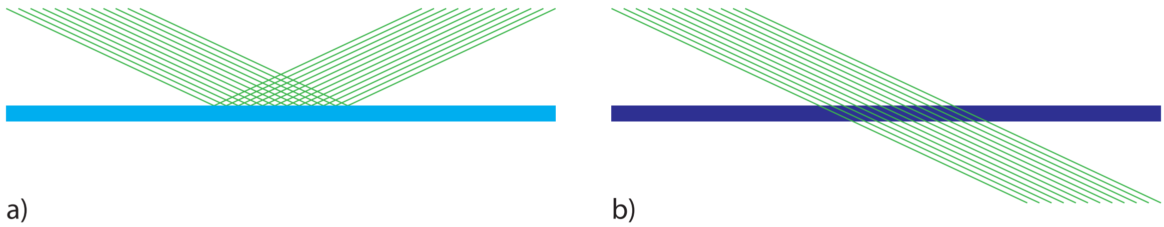

Figure 1: Illustration of operation principle. Incident light rays hit a microfluidic channel. Depending on the refractive index of the liquid in the channel rays are either totally reflected or transmitted. a) Low refractive index solution (e.g., DI-water) results in light reflection at the solid-liquid interface. b) High refractive index solution allows incident light to penetrate the channel.

At the presented device two microfluidic channels are placed after each other (following the path of light). In that way three distinct positions for the light on-chip can be configured. To allow for an accurate determination of the optical signals, glass fibers were aligned at those three positions to collect the exiting light. Compared to other on-chip light modulation approaches this principle is contact-free, lacking any mechanically moving parts. In that sense wearing can be excluded and infinite switching sequences are possible.

2. FABRICATION

Devices were fabricated in polydimethylsiloxane (PDMS) using soft lithography. For the master device fabrication negative dry film resists, Ordyl SY330 and Ordyl SY317 (ElgaEurope, Italy) having a thickness of 30 µm and 17 µm, respectively, are used. The fabrication process for the devices is divided into six main steps (Fig. 2). For other applications and more detailed information about this fabrication method the reader is referred to literature [6, 7, 8].

A one-sided polished 4 inch silicon wafer is used as a substrate for the devices. At first, a 17 µm Ordyl layer is laminated onto the silicon wafer (Fig. 2a). After lamination, the wafer is flood exposed to UV light for 30 s (mask aligner MA150M, SÜSS, Germany, Fig. 2b). This layer improves the adhesion of following layers, allowing for the realization of higher aspect ratios. In the next step multiple Ordyl layers are laminated (total thickness of 107 µm) on top of the 17 µm Ordyl layer (Fig. 2c). Using a high-resolution printed foil mask (64000 dpi) the microfluidic and optical elements are structured into the 107 µm thick Ordyl layer (UV exposure for 35 s; Fig. 2d). After a post exposure bake (1 min at 85°C), development is performed under ultrasonic agitation for 60 s in Ordyl developer (xylene, 2-butoxyethylester, and ethylbenzene, 56/30/14, v/v/v; Fig. 2e).

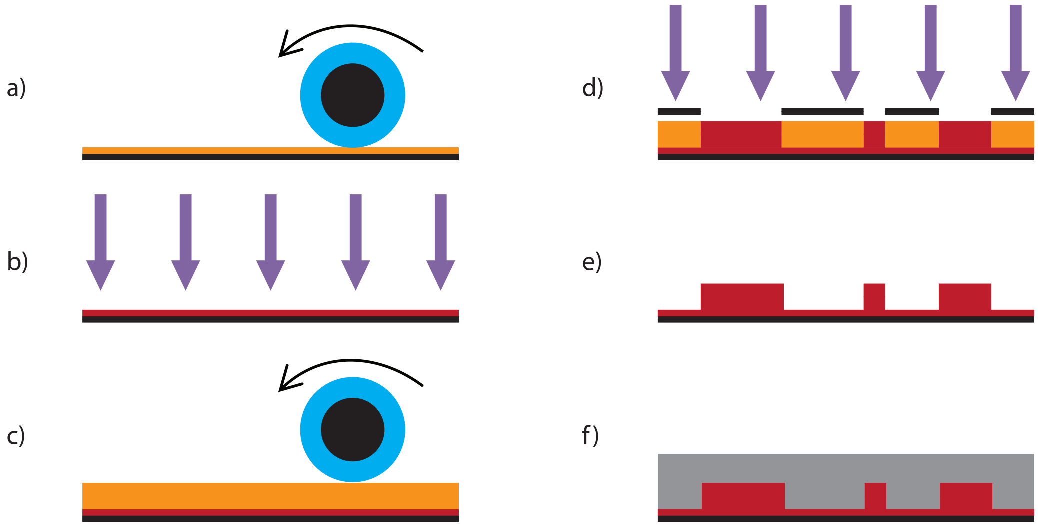

Figure 2: Process steps for the fabrication of master devices and successive PDMS casting; a) 17 µm thick dry resist layer is laminated onto a one-sided polished 4 inch silicon wafer, b) flood UV exposure of the 17 µm layer for 30 s to improve adhesion of following dry resist layers, c) consecutive lamination of four dry resist layers (one 17 µm and three 30 µm) to reach final structure height of 107 µm, d) UV exposure (35 s) through a high resolution printed foil mask (64000 dpi) to structure elements, e) after post exposure bake (1 min, 85°C) ultrasonically actuated development of structures in dry resist developer for 60 s, f) final PDMS casting following standard protocols.

The final step is PDMS casting (Fig. 2f) following standard procedures. To seal the microfluidic channels the PDMS devices were irreversible bonded on glass microscope slides after activation of the PDMS surface by oxygen-plasma. Holes were punched through the top PDMS layer to provide fluidic in- and outlets.

3. RESULTS AND DISCUSSION

To evaluate the performance of the developed device de-ionized (DI) water and a 5 mol/L $CaCl_2$ solution were used as the low (n of 1.33) and as the high (n of 1.45) refractive index medium, respectively. Instead of DI-water air could be used as well providing an even lower refractive index (n of 1.00). Anyway, to ensure a smooth interface between PDMS (n of 1.41) and the medium in the channel fluids are more suitable than gases. An external laser module (531 nm, 20 mW, Roithner, Austria) was used as light source. Peripheral light guiding was managed by reduced cladding glass fibers (inner diameter of 50 µm, outer diameter of 90 µm; Polymicro Technologies USA) which were clamped onto the device using integrated fiber grooves. At the three output-glass fibers silicon photodetectors (Thorlabs, USA) were attached.

Fig. 3a depicts ray-tracing simulations of the three distinct switching states. An integrated waveguide and micro-air lenses manage on-chip light confinement and focusing in-plane (two dimensions). In the current design there is no light confinement in the third dimension. As can be seen in the figure, at a low refractive index medium (illustrated in light blue) light is totally reflected while at a high refractive index medium matching the index of PDMS (illustrated in dark blue) light is entirely transmitted. In Fig. 3b corresponding fluorescence images of the chip are depicted for each of the three switching states. For those images the PDMS device was soaked with a fluorophore (Rhodamine B) to allow for visualization of the light path on-chip by exciting fluorescence.
In Fig. 3b1 the first channel is filled with DI-water at which most light is reflected and output 1 is activated. In this case the second channel has no influence on the output. It can be filled with either DI-water or a $CaCl_2$ solution. Due to the lacking confinement in the third dimension there are also light rays visible crossing the channel. By changing the constitution of the device (sandwich structure) light confinement could be realized in this third dimension as well which would further improve the performance of the device. Fig. 3b2 depicts the situation if the first channel is filled with a $CaCl_2$ solution and the second channel is filled with DI-water. There are no light rays reflected by the first channel anymore. At the second channel total internal reflection occurs and the output 2 is activated. The third switching state (Fig. 3b3) is obtained if both channels are filled

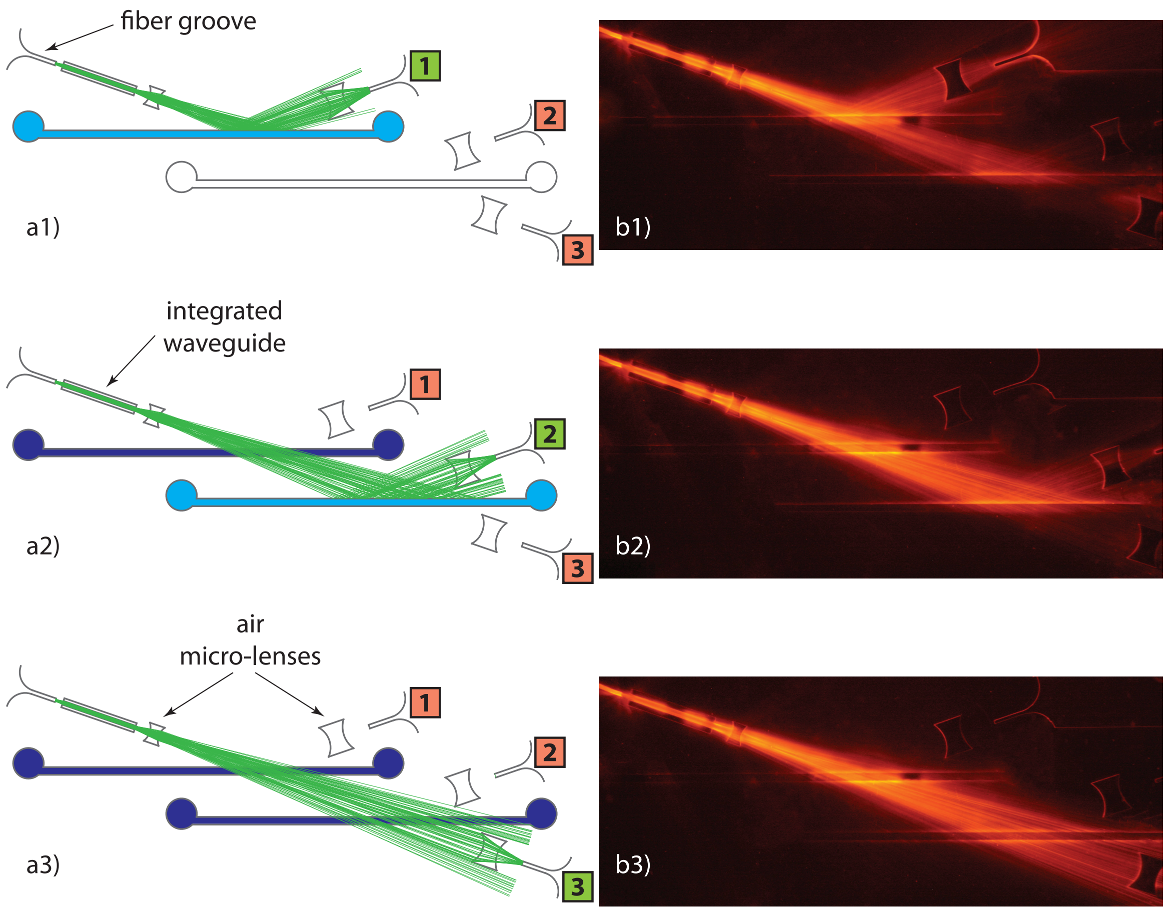

Figure 3: Illustration of on-chip light switching process. a) Simulation results and b) corresponding fluorescence images of three distinct switching states. In a1) and b1) the first channel is filled with DI-water (low refractive index) resulting in light reflection upwards and output 1 is activated. In a2) and b2) the first channel is filled with $CaCl_2$ solution (high refractive index) allowing light to penetrate through while the second channel filled with DI-water reflects the incident light and output 2 is activated. In a3) and b3) both channels are filled with $CaCl_2$ solution allowing light to penetrate through both channels and output 3 is activated.

with $CaCl_2$. In that case output 3 is activated. This principle can be extended by implementation of additional microfluidic channels.

In a final experiment the output signals of the three photodetectors (each representing one optical output) were recorded by an oscilloscope. The obtained results are shown in Fig. 4. Depending on the solutions in the two microfluidic channels (see table 1) one of the three outputs is at its maximum and activated while the other two are disabled. In the switching states I & V both channels are filled with DI-water and output 1 is high. At state IV the first channel is filled with DI-water and the second channel is filled with $CaCl_2$ solution. The difference compared to states I & V is the level of output 2 and output 3. In theory those outputs are not influenced, but in practice, due to the missing confinement in the third dimension, there are small changes evident. In state II & VI the $CaCl_2$ solution is filled in the first channel and DI-water in the second which sets output 2 at its maximum. For state III both channels are filled with $CaCl_2$ solution and output 3 is activated. The overshoots at the beginning of each state are explained by the transition of one medium to the next one. At this interface light is reflected in all directions and short variations in the signals occur. For fluorescence applications this is of minor importance.

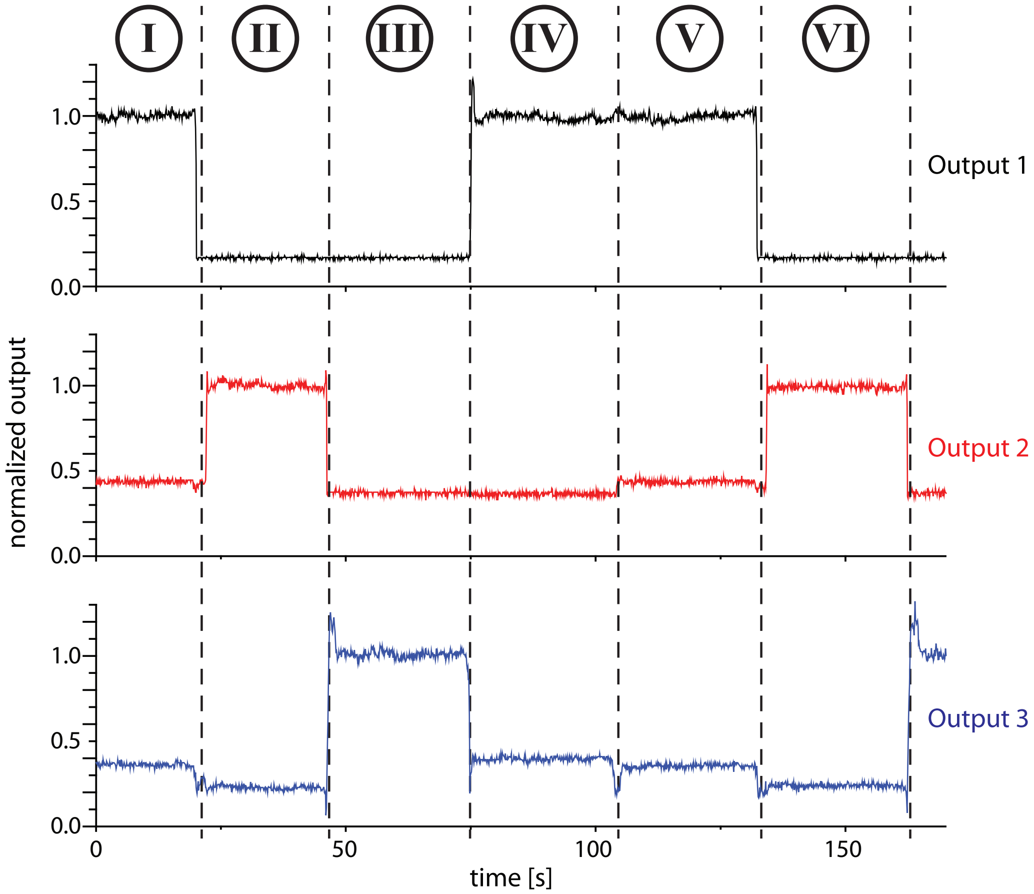

Figure 4: Output signals of the photodetectors. Depending on the solutions filled in the channels one of the three outputs is activated (high output signal). DI-water was used as low refractive index and a $CaCl_2$ solution as high refractive index medium. See table 1 for the solutions in the channels at each labeled state.

	State I	State II	State III	State IV	State V	State VI
Channel 1	DI	$CaCl_2$	$CaCl_2$	DI	DI	$CaCl_2$
Channel 2	DI	DI	$CaCl_2$	$CaCl_2$	DI	DI

Table 1: Filling solutions of the microfluidic channels for the six switching states labeled in Fig. 4

4. CONCLUSIONS

A robust and simple device for contact-free on-chip light switching has been elaborated. Consisting of just a few elements, this method can be easily integrated on other microfluidic analysis devices. Especially for fluorescence applications the control over the light position is essential. Furthermore, limiting the time of exposure of the analyte can reduce photo bleaching effects to a minimum. In that sense, fluorescence analysis devices could benefit from the implementation of an on-chip light modulation unit. Compared to devices implementing mechanically moving parts for light switching, wearing and failure due to sticking can be entirely excluded using the proposed principle. The consumption of liquids is kept at a minimum since there is no need for a permanent flow through the device once the desired light position has been reached. Considering those advantages this principle can be an enhancement for many microfluidic devices having optical mechanisms for the analysis implemented.

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