

# Novel Design of Additively Manufactured Micromixer in a Microchannel Comprising Mounting and Sealing Elements <sup>†</sup>

Martin Oellers <sup>1,2,\*</sup>, Frank Bunge <sup>1,2</sup>, Frieder Lucklum <sup>1,2</sup>, Sander van den Driesche <sup>1,2</sup> and Michael J. Vellekoop <sup>1,2</sup>

<sup>1</sup> Institute for Microsensors, -actuators and -systems (IMSAS), University of Bremen, 28359 Bremen, Germany; fbunge@imsas.uni-bremen.de (F.B.); flucklum@imsas.uni-bremen.de (F.L.); sdriesche@uni-bremen.de (S.v.d.D.); mvellekoop@imsas.uni-bremen.de (M.J.V.)

<sup>2</sup> Microsystems Center Bremen (MCB), 28359 Bremen, Germany

\* Correspondence: moellers@imsas.uni-bremen.de

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**Abstract:** An additively manufactured three-dimensional mixing element (3DME) integrated in a microchannel is presented. The 3DME increases the interfacial contact-surface by swapping the positions of the incoming streaming liquids. The novel design incorporates important design alterations to a prior prototype. These alterations significantly improve the integration of microelements written by two-photon polymerization (2pp) into photolithographically defined microchannels. Anchor-structures for increased strength as well as a roof to compensate for height-discrepancies between the lithographically defined microchannel and the 2pp-written 3DME are addressed. These allow for a better positioning as well as an increased sealing reliability between the top of the 3DME and a PDMS-lid which in our case is used to close the microchannel.

**Keywords:** micromixer; swap mixer; two-photon-polymerization; additive manufacturing

## 1. Introduction

Passive microfluidic mixers are important devices when two or more liquids have to be mixed with each other specifically, in the regime of laminar flow and small volumes of sample liquids. In the past many concepts and devices have been developed and researched [1–3]. This is also because of a vast landscape of fabrication methods such as standard microfabrication (photolithography, reactive ion etching, wet-etching) as well as laser-writing [4] and more recently 3D additive manufacturing [5].

Commonly, standard microfabrication methods allow for the fabrication of micromixers in a horizontal geometry where e.g., liquids can be stacked on top of each other. An example is a wedged micromixer fabricated in silicon where two liquids are divided in four thin horizontal layers for fast mixing [6].

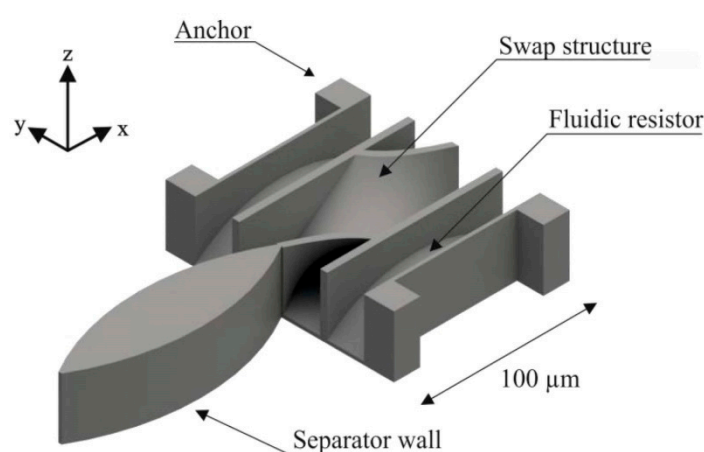
However, the horizontal mixing of liquids has some disadvantages. Optical inspection without the use of fluorescence or Raman spectroscopy on layers of horizontally aligned liquids is quite problematic. Therefore, it is desirable to observe the quality of mixing of vertically aligned liquid layers by optical microscopy.

Also, the quality of mixing is dependent on the number of liquid layers. The mixing performance increases when the thickness of liquid layers decreases because the diffusion length of a solvate into a solvent is a fixed material property. Therefore, if the layer thickness of the adjacent liquid layers is decreasing, the liquids mix faster.

Technological advances in the field of additive manufacturing, especially two-photon-polymerization (2pp) [7] allow for the integration of 3D- structures in pre-fabricated microchannels [5]. Here, the free-form CAD-design of additive manufacturing allows for the fast integration and iteration of new designs into structures that have been fabricated in bulk (which in our case are photolithographically fabricated microchannels). Furthermore, the full control over the geometric orientation and therefore in the case of laminar mixing, the layer thickness of liquids can be adjusted down to a few micrometers. The writing speed in recently available systems can be so high that complex structures are written within a few minutes, which makes an additive approach also attractive for wafer-scale processing.

## 2. Design and Fabrication

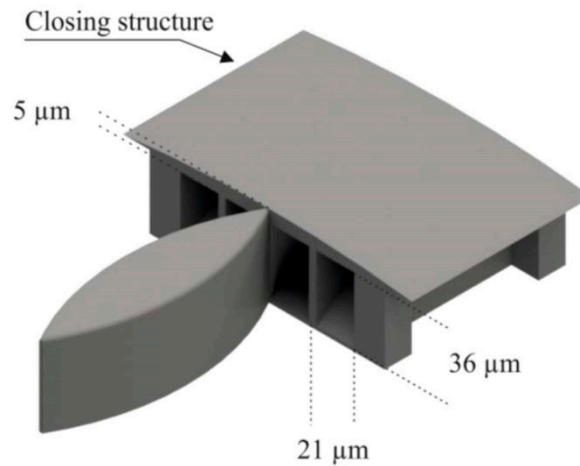
Here we present a design alteration of a previously reported 3DME [8]. We reported on a microfluidic swap-structure where a microelement is integrated into a microchannel that swaps the position of two of four inlets. The interfacial surface between the incoming liquids A and B is tripled (AABB  $\rightarrow$  ABAB). Therefore, a faster mixing process can be achieved if the number of swaps is increased further. Figure 1 shows a novel CAD design of a 3DME. At first, we added a separator wall that prevents the incoming liquids in the microchannel from undefined mixing at the interface of the liquids before the 3DME. Figure 1 also shows the already presented swap structure as well as the fluidic resistors. The latter are placed in the outer channels to match the pressure drop along all channels so no channel is preferred due to a lower fluidic resistance. COMSOL simulations are performed to determine the optical height of the fluidic resistor.



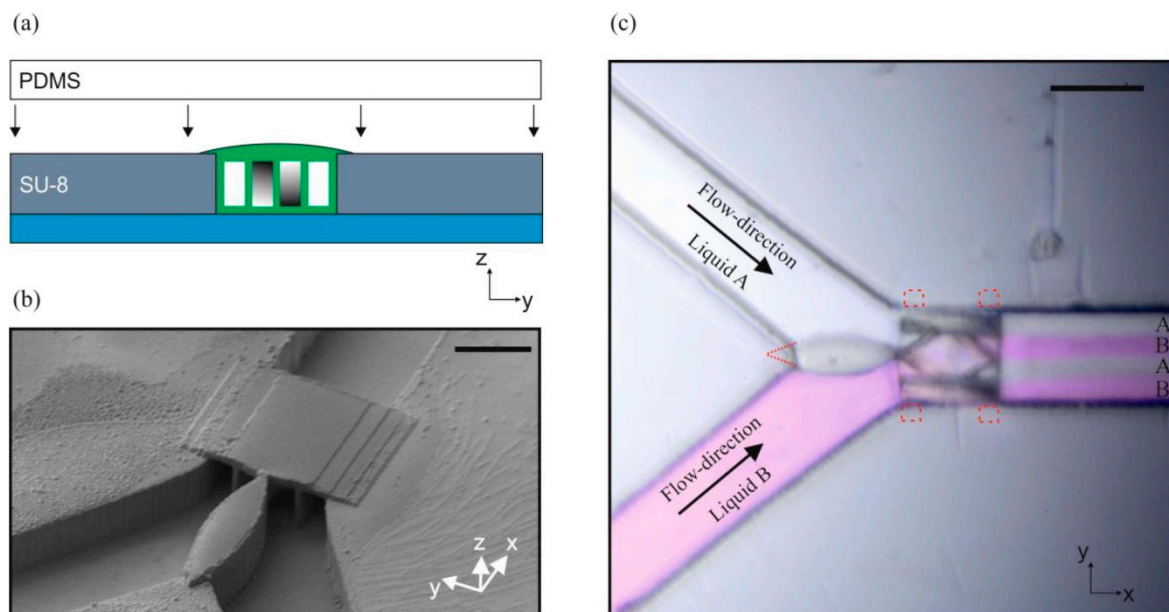
**Figure 1.** CAD rendering of the novel three-dimensional mixing element showing a cut along the xy-plane to show the swap-element and fluidic resistors.

Furthermore, anchors are added to the side of the structure to increase the adhesion between the 3DME and the sidewalls of the lithographically defined microchannel. Therefore, the structures remain in the microchannel even when applying high flow-rates or during nitrogen-drying after development.

Figure 2 shows the closing-structure that has a maximum height of 5μm and is used to facilitate the fluidic closing of the microchannel. From our experience there are always small discrepancies in the height of the microchannel, thus this closing allows for a smooth transition to the channel walls and PDMS-lid which is used as a sealing (see Figure 3a).



**Figure 2.** CAD rendering of the full 3DME with closing structure to enhance the transition from the microelement to the walls of the microchannel as well as fluidic sealing for the PDMS lid.



**Figure 3.** (a) Schematic side-view of the yz-plane to show the functionality of the closing structure. (b) Scanning electron microscopy image of the integrated structure into the microchannel. The separator and the closing structure are well connected to the lithographically defined microchannel. The scale bar at the top right is 50  $\mu\text{m}$ . (c) Optical image showing the functionality of the 3DME for de-ionized water (liquid A) and de-ionized water stained with Rhodamine B (liquid B). The red-dotted lines indicate the position where the anchor-structures and separator wall are embedded into the sidewalls of the microchannel. The scale bar at the top right is 100  $\mu\text{m}$ .

### 3. Methods and Results

A detailed description of the fabrication steps is discussed in [8]. In short, SU-8 photoresist is used to lithographically define a 40  $\mu\text{m}$  high microchannel. Afterwards the 3DME is integrated into the microchannel by two-photon lithography. A scanning electron microscopy image (Figure 3b) shows that the closing structure as well as the separator wall connect well to the sidewalls of the microchannel. Also the functionality of the separator wall becomes evident in Figure 3b. In Figure 3c the cross-over of the anchor-structures as well as the separator wall into the microchannel are indicated by the red dotted lines.

Two liquids enter the 3DME (liquid A: de-ionized water, liquid B: Rhodamine B-stained de-ionized water) and a perfect sample swap result demonstrates the functionality of the design.

#### 4. Conclusions

A refined additively manufactured three-dimensional mixing element (3DME) integrated in a microchannel has been presented. The novel design comprises a previously reported swapping element to increase the interfacial contact-surface by swapping the positions of the streaming liquids. More importantly, in this design anchor-structures for increased strength and adhesion of the 3DME to the walls of the microchannel are added. Furthermore, a roof to compensate for height-discrepancies between the lithographically defined microchannel and the 2pp-written 3DME has been successfully added. These additional elements allow for a better positioning as well as an increased sealing reliability between the top of the 3DME and a PDMS-lid, which is used to close the microchannel.

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