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Rapid, scalable and customizable microfluidic chip design and fabrication via laser cutting for teaching and prototyping

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I. Abstract and Introduction

Microfluidic systems are a growing technology used in biomedical academia and industry for applications in point-of-care diagnostics, high-throughput assays, and wearable devices [1]. Recent advancements in the microfluidics space include organ-on-a-chip models for drug testing and personalized medicine, SARS-CoV-2 screening, and glucose level measurement in blood [1]. The precise design of such devices has traditionally been costly and slow, making prototyping relatively difficult for aspiring students and researchers. Here, we present a complete method for customizable three-layer microfluidic chip fabrication using computer-aided design (CAD) and laser cutting. At a glance, our process creates 25 x 75 mm microfluidic chips by "sandwiching" a precision-cut adhesive layer between a standard microscope slide and an acrylic lid with ports for fluid input and output. Our method is most suitable for use in university makerspaces, laboratories, or workshops with access to tabletop laser-cutter machinery for teaching fluid mechanics and rapid prototyping with scalable subtractive manufacturing. The cutting and assembly process takes about 15 minutes, can be parallelized to manufacture dozens of custom microfluidic devices in a single iteration, and can cut channels as narrow as 100 μm—around the diameter of a human hair—albeit with limited accuracy and some bubble formation. Lastly, the use of industry-standard software and tools makes our protocol more straightforward, reproducible, precise, and extendable for more advanced designs.

II. Results

Figure 1(A) shows five examples of microfluidic chips built using our method with linear, serpentine, spiral, and Y-junction channel structures and widths ranging from 100-700 μm. Fluid flow in microscale channels is characterized by a low Reynolds number; viscous forces dominate compared to inertial forces, resulting in laminar flow and the absence of turbulent mixing, shown in the **Figure 1(B)** micrograph from one of our example devices [2]. **Figure 1(C)** shows an overview of the design and fabrication process; given a finalized CAD file, the laser cutting and assembly process takes around 15 minutes. As previously mentioned, laser cutting is parallelizable; dozens of microfluidic chips can be cut in a single iteration on a laser cutter given the proper amount of material. **Figure 1(D, E)** shows several micrographs from our examples in **Figure 1(A)**; the narrowest channels are formed from the kerf of a single laser cut. Bubbles can often be seen at bends in the channel.

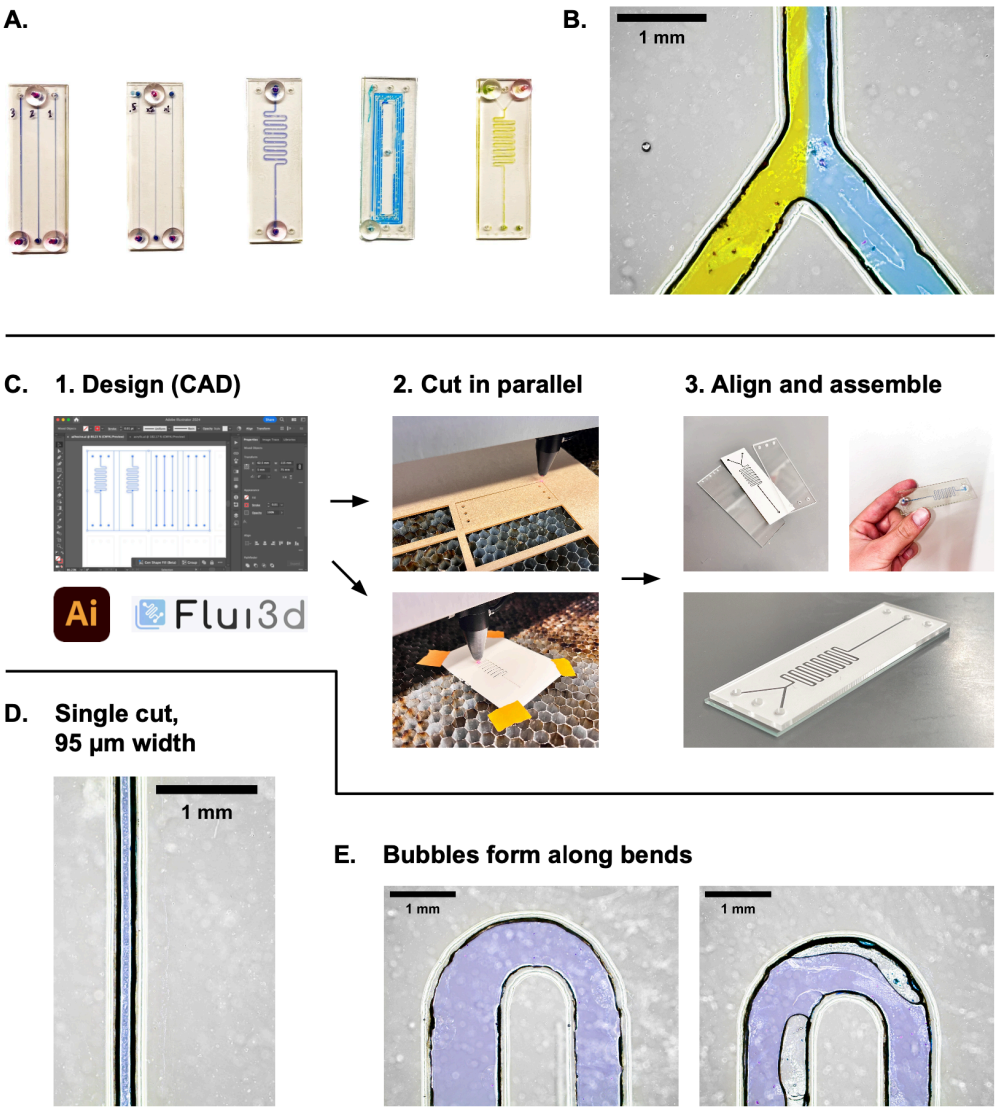

Figure 1. (A) Examples of five microfluidic chips made following our methodology. (B) Y-junction demonstrating laminar flow where two upward-flowing yellow- and blue-dyed streams intersect but do not turbulently mix. (C) Overview of the design and fabrication process. The channel design is cut into the middle adhesive layer only, which is "sandwiched" between a glass slide and an acrylic lid with holes. (D) Micrograph of our narrowest channel formed from the kerf of a single laser cut with an approximate width of 95 µm. (E) Bubbles often form along some bends in serpentine structures, likely due to residual air on the adhesive layer. Note the difference in channel width across the bends due to inaccuracies in adhesive cutting.

III. Discussion

Other techniques that employ blade cutter machines from brands like Cricut or Silhouette are often cheaper and more accessible. However, our method allows for greater precision, simplicity, and reproducibility by only using a laser cutter paired with Adobe Illustrator for manufacturing all custom components. Illustrator allows for complete customization of the channel geometry and is well established as the industry standard software for vector graphics, though it has a greater learning curve than other options.

This protocol is also limited in its fabrication accuracy; the kerf produced from laser cutting at the micron scale results in channel widths that significantly differ from their design specification. For example, a 300 µm channel in CAD resulted in a 400 µm observed channel—see the Data Availability section below for additional imaging. In our testing, for a given laser cutter machine, this bias is consistent between replicates, though further work should be done to quantitatively measure the variance between cuts. The relative error is reduced for larger channel widths. Additionally, some complex designs (i.e., with multiple serpentines) are hard to fabricate due to the fragility of the adhesive layer with our method. Further work to stabilize the adhesive layer while cutting would allow for more intricate designs.

As previously mentioned, bubbles from the assembly process are also common at bends in the microfluidic channels, which obstruct fluid flow and reduce the effective width of the channels. Future work on this front should be done to better remove air pockets in fabrication.

IV. Methods

A. Fabrication

Our design and fabrication process involved three steps: (1) designing the adhesive channel and acrylic lid via CAD software, (2) laser cutting those layers, and (3) aligning and assembling those layers atop a 1 x 3 inch glass microscope slide, as shown in **Figure 1(C)**.

First, Adobe Illustrator (adobe.com/products/illustrator.html) was used for CAD. To align with the glass microscope slide, the adhesive and acrylic layers were designed to be 25 x 75 mm. Three 2 mm-diameter holes were added on both ends of the adhesive and acrylic designs to allow fluid input/output. Lastly, channels were outlined on the adhesive layer design; we set channel widths from 700 µm to 0 µm (a single line) in our examples. See the Data Availability section below for our CAD files. Note that all lines (strokes) have a 0.01 pt width and are colored pure red, which was requisite for vector cutting on our laser cutting machine.

Flui3d (flui3d.org) is another CAD software that can be used to easily draft channel designs that can be downloaded as a vector SVG file (under the “Output Options” menu) and directly imported to Adobe Illustrator. Note that Flui3d designs must be rescaled in Adobe Illustrator, and fluid channels must be converted to outlines for laser cutting; this can be done via the *Object* > *Path* > *Outline Stroke* tool.

Next, we used a 10.6 μm 50 W CO2 Universal Laser Systems VLS3.60DT laser cutter to first cut the acrylic layer, and then the adhesive layer from our CAD files. 1.6 mm-thick (1/16 inch) clear acrylic with protective film was used as the lid material. For our laser system, "Cast Acrylic" with 2.00 mm thickness was used as the material setting to cut the lid design into the acrylic layer. After cutting, the protective film was removed from both sides of the acrylic lid.

Adhesives Research Inc. ARcare 90106NB was used as the adhesive material (140 μm total thickness without liners) for our examples, though other adhesive materials may be used. For our laser system, "3M™ Adhesive Transfer Tape- 467MP" with 0.15 mm thickness was used as the material setting to cut the channel design into the adhesive layer. The adhesive material was taped down to the cutting region to mitigate shifting, and the top liner was removed to expose the up-facing adhesive before cutting. After cutting, tweezers were used to remove "negative" material from the channels and end holes, then a glass slide was pressed on the exposed adhesive and the assembly was removed from the laser cutter.

The second liner on the adhesive was then removed and the adhesive layer holes were aligned with the corresponding holes on the cut acrylic lid. The acrylic lid was pressed to the adhesive-glass assembly and we used a roll of tape to remove most air bubbles.

Note that this process allowed for multiple acrylic lids and adhesive channel layers to be cut in a single round with the laser cutter.

Lastly, adhesive silicone bumper pads, often branded for cabinet or drawer dampening, were punctured (i.e., with a biopsy punch) to facilitate the connection of a syringe or pipette to push fluid through our microfluidic channels. These pads were adhered to the input/output holes on the acrylic lid layer and a micropipette was used to push dyed water into our assembled microfluidic chips.

B. Microscopy and Image Analysis

Adobe Lightroom (adobe.com/products/photoshop-lightroom.html) and FIJI (imagej.net/software/fiji) were used to process all images [3]; Adobe Lightroom was solely used to adjust brightness, white balance, and contrast for better visibility. Micrographs of the channels in **Figure 1(B)** and **Figure 2(B, C)**, were taken using an Invitrogen EVOS XL Core Configured Cell Imager microscope with a 4x objective. FIJI was used to add 1 mm scaling bars to the micrographs and measure channel widths [3].

C. Data Availability

All CAD files required for laser cutting are available as Adobe Illustrator (".ai") files on our GitHub repository (github.com/robertheeter/diy-microfluidics). This repository also contains supplementary images, figures, and datasheets from this exercise.

V. References

[1] Deliorman, M., Ali, D. S., & Qasaimeh, M. A. (2023). Next-generation microfluidics for biomedical research and healthcare applications. *Biomedical Engineering and Computational Biology, 14*, 11795972231214387. https://doi.org/10.1177/11795972231214387

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