

Low-cost fabrication and performance testing of Polydimethylsiloxane (PDMS) micromixers using an improved print-and-Peel (PAP) method

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Abstract. The research presents different configurations of microfluidic mixers made from polydimethylsiloxane (PDMS) fabricated using an improved, low-cost print-and-peel (PAP) method. Processes, such as mixing, operated in the micro scale allow decreased equipment size-to-production capacity ratio and decreased energy consumption per unit product. In the study, saturated solutions of blue and yellow food dyes were introduced inside the channels using a LEGO® improvised microsyringe pump. Scanning Electron Microscopy (SEM) was used to determine the average depth of the fabricated micromixers which was found to be around 14 μm . The flows were observed and images were taken using a light microscope. The color intensities of the images were then measured using MATLAB®. From the relationship between color intensity and concentration, the mixing indices were calculated and found to be 0.9435 to 0.9941, which falls within the standard mixing index range (0.8 – 1.0) regardless of the flow rate and the configuration of the micromixer as verified through the two-way ANOVA. From the cost analysis, the cost of the device fabricated in this study is a hundred-fold less than expenses from standard fabrication procedures. Hence, the fabricated device provides an alternative for micromixers produced from expensive and conventional lithographic methods.

1. Introduction

Microfluidics is a branch of science that deals with the design, fabrication, and manipulation of very small amounts of fluid flow particularly in the microscale [1]. Principles of microfluidics were first utilized in manufacturing inkjet printers during the 1950s, and has extended its applications as of today to various fields such as process intensification, diagnostics, and microelectronics [2].

When working with microfluidic systems, the surface area-to-volume ratio is increased due to its very small characteristic length. Because of the more dominant effects of viscous forces than body forces in these systems, diffusion predominantly works over convection in which components can maximize the effects of diffusion. Processes involved in food processing and pharmaceutical industries which need high viscosity and slow velocities are easier to manipulate in the microscale. Also, the gradients are predictable which gives room for more accurate control over the fluids being mixed [3].

Techniques such as lithographic and non-lithographic methods can be used to fabricate microfluidic devices. Non-lithographic methods offer low-cost fabrication, access to a broader range of materials, and simplicity and flexibility in pattern forming as opposed to photolithography, which is a conventional fabrication technique [4, 5, 6, 7, 8]. Silicon chips are used as the primary material in



microfluidic devices. Alternatives to silicon such as polydimethylsiloxane (PDMS) can be utilized to reduce the cost of production. PDMS is usually chosen as the substrate because it is transparent over a wide range of optical frequencies, is biocompatible, and is relatively inexpensive [4].

Conventional fabrication techniques for microfluidic devices such as photolithography are not only costly but also labor-intensive. These methods involve the use of specialized equipment and conditions which limit large-scale production. Developing and improving inexpensive methods will allow more devices to be fabricated easier which will make this technology more accessible to scientists and researchers in low resource countries such as the Philippines.

Some recent researches investigate the ability of office printers in producing the master for microfluidic device fabrication. The desired device pattern is etched onto the master using the printer. PDMS is cured over the pattern to allow the transfer of design from the master to the substrate surface. Reference [4] proposed a low-cost microchannel fabrication by improving the print-and-peel method upon using an inkjet printer. For this proposed microchannel fabrication process, microfluidic devices should be fabricated to demonstrate the validity of this process.

The research aims to fabricate low-cost working micromixers of different configurations and to determine the performance of the fabricated working micromixers. Specifically, this study targets to quantify the mixing index of the fabricated working micromixers through colorimetry, to compare the mixing indices of the fabricated micromixers to existing literature values, and to identify the best configuration among the fabricated micromixers according to their mixing index.

This study is limited to three design configurations used by reference [9]. In fabricating the micromixers, the material used is PDMS and the fabrication method used is adapted from reference [4]. The channel width, aspect ratio, and smoothness of the walls are dependent on AutoCAD® 2015 thinnest preset line and Canon iP 2870. The designs of the mixer were selected according to the limitations of the printer. A glass slide is used as base for the micromixers. The surfaces of both the glass slide and PDMS are subjected to oxygen plasma.

To benchmark the fabricated low-cost micromixers, the fluids used by reference [10] are followed, which are saturated solutions of yellow and blue food dye. These fluids are introduced inside the system using an improvised microsyringe pump made from LEGO® Mindstorms® NXT Kit and programmed using LabVIEW®. The mixing index is determined via colorimetry. Images were taken upon achieving steady-state conditions by the optical microscope. MATLAB® R2011a is used for image processing and analysis. The obtained mixing indices were compared to the standard provided by reference [10].

2. Methodology

2.1. Mold fabrication

Using the thinnest preset line of AutoCAD® 2015, three different micromixer designs from reference [9] are replicated as shown in figure 1.

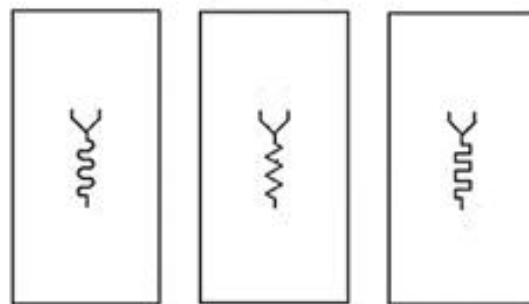


Figure 1. Design configurations (from left to right: curve-wave, zigzag, square-wave).

The designs are printed on matte sticker paper using a Canon iP 2870 inkjet printer. To increase the depth of the micromixer channels, the designs are repeatedly printed eighty-six (86) times on a single sheet of sticker paper. The operation of the printer is manually modified using a metal wire such that the printing job would not require multiple sheets of paper [4].

The number of overruns, which is the number of times of repeated printing was optimized from reference [4]. The fabricated microchannels are expected to have an aspect ratio of 0.07, which is the average ratio of the depth over the width of the microchannels. The printed molds were left inside a clean bench to dry at atmospheric conditions for at least 12 hours.

2.2. Preparation and curing of PDMS

The PDMS solution was prepared using a 10:1 mass ratio of polymer base-to-curing agent. Considering that the optimum device height is 3 mm based from reference [4], the required mass was obtained by multiplying the density of PDMS (1030 kg/m^3) with the optimum device height of 3 mm and the container area.

For every 6 grams of polymer base, the PDMS solution prepared using a plastic cup and a coffee stirrer is mixed for 2 minutes. Meanwhile, the printed molds are peeled from the sticker paper and placed onto a polystyrene container wrapped with an aluminum foil. The prepared PDMS solution is then evenly poured into the container.

Using a vacuum oven, the PDMS is subjected to a one-hour degassing process to remove trapped air. This is followed by a 90-minute curing process at 100°C under atmospheric conditions. Afterwards, the cured PDMS is cooled to room temperature for 45 minutes.

2.3. Building the micromixer

The cured PDMS, where micromixer channels are now etched, is peeled from the container. Devices are cut accordingly from the whole cured slab of PDMS. At the ends of the channels, holes are created using an improvised puncher where silicon microtubes will be attached.

The adhesion between the surfaces is induced using plasma treatment. Both the channel and the glass slide are washed with ethanol before exposing to oxygen plasma (120 seconds, 320 Pa, 50 W). The exposed surfaces are then made to contact with each other immediately after treatment. Microtubes are then attached to the holes at the ends of the channels using an adhesive.

2.4. Conducting the test runs

Saturated solutions of blue and yellow colored dyes were prepared and loaded to the improvised microsyringe pump constructed using LEGO® Mindstorms®. The mixing is observed using a Euromex Novex optical microscope as the improvised pump introduces the colored dyes into the channels.

3. Results and discussion

3.1. Channel characterization using Scanning Electron Microscopy (SEM)

Samples were cut to get the cross-sectional view of the channels. The exposed cross-section was coated with platinum and subjected to SEM. The width and depth were measured for each sample and the average measurements are presented in table 1.

Table 1. Average channel cross-sectional dimensions.

Micromixer channel configuration	Square-wave	Curve-wave	Zigzag
average channel width, μm	223.12 ± 48.44	186.32 ± 41.14	159.84 ± 33.52
average channel depth, μm	13.36 ± 6.01	13.09 ± 4.11	14.88 ± 3.52

Figure 2 shows some of the SEM images taken in getting the cross-sectional dimensions of the fabricated micromixers.

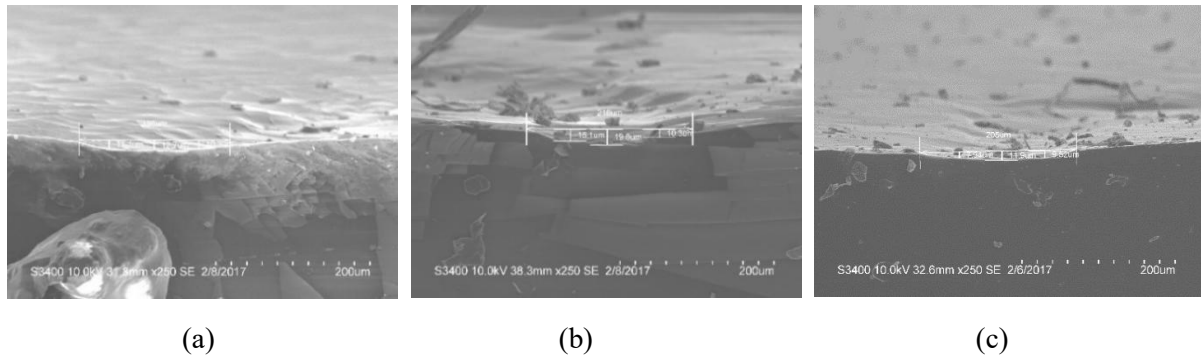


Figure 2. Cross-section of the channels taken using SEM (a –zigzag, b –curve-wave, c –square-wave).

3.2. Channel characterization using Scanning Electron Microscopy (SEM)

Figure 3 shows the images of the actual flow inside the channels. Analysis is done by subjecting the images of the flow to colorimetry wherein the color intensities are used to describe the mixing behavior inside the channel. The green-colored area between yellow and blue areas is the region where the two fluids mix. The behavior of this mixing region can be related to the extent of diffusive mixing inside the channel.

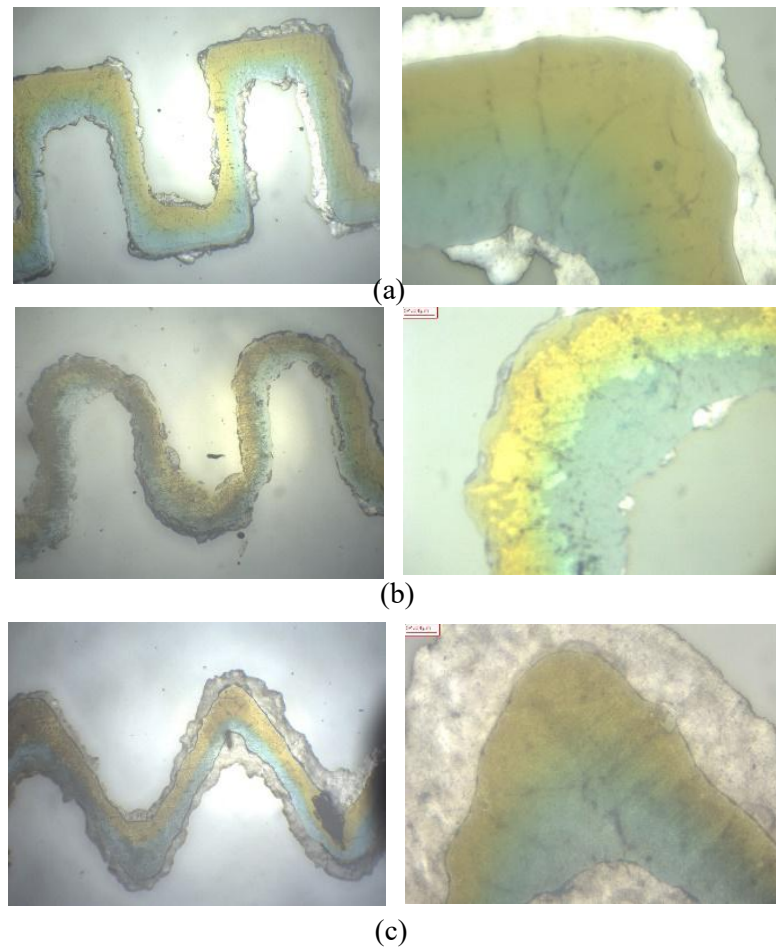


Figure 3. Images of the actual flow (left at 50x magnification, right at 200x magnification; a –square-wave, b –curve-wave, c –zigzag).

The grayscale intensity value of the green region of each image was determined using MATLAB®. Using this grayscale value, the width of the mixing region was determined by measuring the length of the segment having the same intensity value of the green region. The span of the mixing region was taken at several points along the length of the channel.

Figure 4 shows the graphs of the span of mixing plotted against the projected distance. Generally, the mixing region increases in width along the projected distance inside the channel. The projected distance is the unstretched length of the channels from the first point of contact of the two fluids. This shows that there is an increase in the diffusive mixing as the fluid flows across the channel.

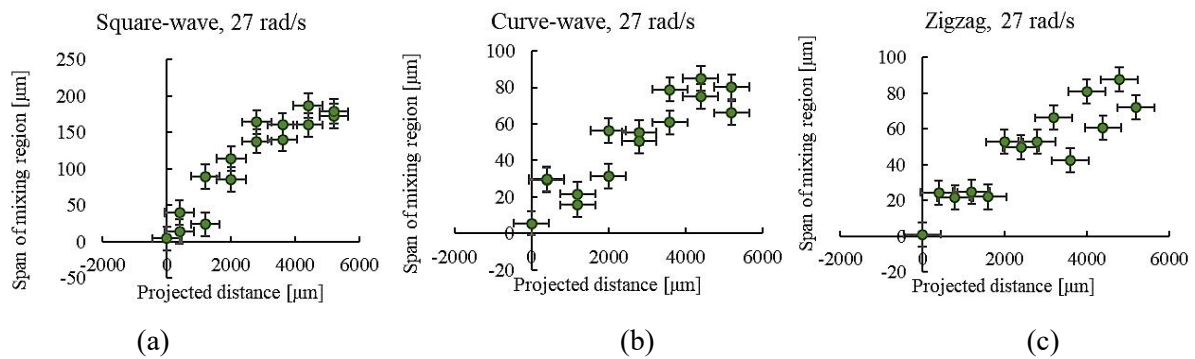


Figure 4. Span of mixing region plotted against the projected distance (a –square-wave, b –curve-wave, c –zigzag).

The extent of mixing was quantified by finding the mixing index at the end of the channel. Mixing index is a quantification of the extent of mixing ranging from 0, unmixed, to 1, completely mixed. Using the grayscale image of the channel, the color intensity gradient across the width was obtained. The intensity values were then converted to concentration and from the concentration gradient, the mixing index was calculated. Average values are tabulated in table 2.

Table 2. Average mixing indices.

Micromixer channel configuration	Square-wave	Curve-wave	Zigzag
Low-speed (27 rad/s)	0.9745 ± 0.011	0.9893 ± 0.005	0.9785 ± 0.023
Mid-speed (392 rad/s)	0.9774 ± 0.002	0.9755 ± 0.003	0.9782 ± 0.008
High-speed (703 rad/s)	0.9751 ± 0.027	0.9805 ± 0.006	0.9980 ± 0.003

3.3. Hypothesis testing

An F-Test using the two-way ANOVA is conducted to check if a significant relationship exists between the independent variables, (1) mixer configuration and (2) speed at which the fluids are introduced to the mixer, and the dependent variable, which is mixing index.

The following list shows the null hypotheses tested:

- $H_{0,1}$: There is no significant relationship between the mixing index and the speed at which the fluids are introduced.
- $H_{0,2}$: There is no significant relationship between the mixing index and the configuration of the mixers.
- $H_{0,3}$: There is no significant relationship between the mixing index, the speed at which the fluids are induced, and the configuration of the mixers.

Table 3 shows the results of the ANOVA conducted. Upon comparing the F-values calculated and the values from the F-table, it is found that neither of the factors nor its interaction have a significant relationship to the obtained mixing indices.

Table 3. Calculated F values.

Parameter	Calculated F values	F value from table	Accept/Reject H_0
F_{speed}	0.355	3.555	accept H_0
$F_{\text{configuration}}$	0.733	3.555	accept H_0
$F_{\text{interaction}}$	0.711	2.983	accept H_0

3.4. Cost analysis and literature comparison

The cost analysis conducted was based on the study of references [4] and [11]. The cost of fabricating a single micromixer using the improved PAP method was compared to the cost of fabricating one wafer of UV LIGA SU-8. The latter was chosen as the representative of photolithography as it is one of the most common techniques used [11]. Equation (1) was used to obtain the cost per unit of device for each mentioned fabrication method:

$$C_M = \frac{C_F}{N} + C_V \quad (1)$$

where C_M is the cost per unit of a method, C_F is the fixed cost, N is the number of units, and C_V is the variable cost per unit. C_F includes the capital costs of equipment used in fabrication while C_V includes the consumables and operating expenses of the equipment per unit.

Accounted in the capital cost of this study is the inkjet printer. The variable cost consists of the black pigment-based ink, glossy-type sticker paper, and electricity consumed during the printing of the molds and the plasma treatment. Table 4 shows that the improved PAP method is a hundred-fold cheaper compared to conventional photolithography.

Table 4. Cost comparison.

	Improved PAP	UV Liga SU-8
Capital Cost (Php)	1,895	10,209,063
Variable Cost (Php per channel/wafer)	0.15	125.08

In terms of mixing index, the range of mixing indices from the multiple combinations of three different configurations at low, mid and high speed were found to be from 0.9435 to 0.9941. This range falls within the standard mixing index for micromixers which runs from 0.8 to 1.0 [10]. Additionally, a passive micromixer with zigzag channels was reported to have a mixing index of 0.96 [10]. In comparison, the mixing indices obtained from this study are within $\pm 3.5\%$ of 0.96.

4. Conclusion and recommendations

Working micromixers of three different configurations, namely the square-wave, the curve-wave, and the zigzag, have been successfully fabricated. For each configuration, successful mixing of the fluids was observed within the range of speeds induced by the microsyringe pump. Mixing indices were obtained and were found to fall within 0.9435 to 0.9941.

The zigzag configuration gave the highest mixing index values. However, upon conducting F-Test using ANOVA over the pool of data obtained, it is determined that there is no significant relationship between the mixer configuration, the speed induced by the microsyringe pump, and the mixing index.

Given that there is no significant relationship between the factors mentioned, a mixing index within the standard range could be obtained from the micromixers fabricated using this low-cost method, regardless of the mixer configuration and the speed at which the fluids are induced. Additionally, cost analysis shows that fabrication cost per device is 0.15 Php, which is a hundred-fold less than a microfluidic device produced using conventional lithographic methods.

For future studies, it is recommended to work in a cleaner environment to minimize the impurities to which the channels would be exposed. Other configurations and other fluids could also be tested to confirm the validity of the process for the other possible applications of micromixers.

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