Design and simulation of passive micromixers with ridges for enhanced efficiency

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Abstract. Uniform and rapid mixing between various streams in a microfluidic device is essential for the development of device involving reaction between multiple streams. In this work, microfluidic channels of various geometries were designed and their fluid flow patterns were analyzed to optimize complete mixing of different fluids. The designs were modified by incorporating different types of ridges (square, curved and triangular shaped) in the microfluidic channels. Numerical analysis of the designs was carried out using COMSOL Multiphysics 4.3a. The extent of mixing in each of the design was calculated and the optimized design was fabricated using photolithography followed by soft lithography. The performance of the developed micromixer was studied using colored solutions and it was found to be in good agreement with the simulated results.

Keywords: Microfluidics, Comsol multiphysics, micromixers, photolithography

1. Introduction

Microfluidics is a multidisciplinary field with an increasing relevance in the field of engineering, physics\textsuperscript{1}, chemistry\textsuperscript{2}, biology\textsuperscript{1, 2}, nanotechnology and biotechnology. This branch of science emerged in the beginning of 1980s and is used for a variety of different applications such as DNA chips\textsuperscript{3}, lab on a chip technology\textsuperscript{4}, micro propulsion\textsuperscript{5} and micro thermal technologies\textsuperscript{6}. By understanding the micro scale fluid behaviour microfluidics can be used for studying processes and experiments not possible in the macroscale.

Fluid flow in the microfluidic regime is dominated by viscous forces over inertial forces as the Reynolds number\textsuperscript{7} is very low. One of the most important features is the laminar flow in the microfluidic dimensions. The major challenge associated with this flow pattern is the microfluidic mixing. As the flow is primarily laminar\textsuperscript{8}, fluid streams flow parallel to one another and mixing between the streams take place only by diffusion. Diffusion is a slow process and hence chaotic advections must be introduced into these channels to enhance their mixing efficiency.
Micromixers are specially designed structures that help in inducing chaotic advections[9] within the flow channel by decreasing the total length of the fluid path while increasing the contact time between the fluid streams in a laminar flow. Mixing in microfluidic devices can either be active mixing or passive mixing[10]. In active mixing, an external energy source is provided to enhance the mixing efficiency such as the electro kinetic forces[11], ultrasonic vibrations[12], magnetic forces[13], etc. But the difficulties associated with the integration of active mixers make passive mixers a better choice.

Mixing efficiency in a passive micromixer is increased by modifying the geometry of the microfluidic channels such that the laminar flow is perturbed. Numerous studies have been done on passive mixers to improve the mixing efficiency. In geometries with straight channels such as the T-shaped and Y-shaped channels, efficient mixing requires a very long time[14]. This is because the liquid layers flow parallel to each other with only diffusion taking place between the liquid layers. Mixing efficiency can only be enhanced if we increase the residence time of the fluids within the channels[15]. From the flow visualization experiments done on many modified geometries, it was found that the 3D serpentine channels showed better mixing efficiency compared to the square wave and the straight geometries[16]. The efficiency of these microchannels increases with Reynolds number due to the presence of eddies formed at the channel bends. The meander channels with diameters in the ratio 1:2 showed enhanced mixing compared to the other serpentine geometries within a shorter length of the microchannel[15]. Rapid microfluidic mixing was studied by Johnson and Ross. Mixing in this design occurs by lateral transport and so therefore it is not limited by diffusion [17]. The efficiency can further be improved by introducing obstructions in the path of the fluid flow. An innovative passive micromixer using modified Tesla structures was developed by Hong and a very good mixing performance was obtained [18]. Fluid mixing in planar spiral microchannels was developed by Arjun and Victor. At low flow rates diffusion is the primary mechanism by which mixing occurs. At higher flow rates secondary Dean effects come into play and contributes to increased levels of mixing [19]. Ali Asgar developed a micromixer that showed excellent mixing over a wide range of flow conditions by incorporating diamond shaped obstructions within the microchannel to break up and recombine the flow[20]. Mixing efficiency of a T-shaped channel is improved by 50% by introducing six J shaped baffles[21]. Efficiency of a serpentine micromixer is increased by incorporating L-shaped repeating units in the serpentine channels. It was found from their studies that mixing is very sensitive to the geometrical parameters[22]. Afroz Alam performed the analysis of mixing in a curved channel with rectangular grooves and concluded that grooved microchannels produce better mixing efficiency than smooth microchannels[23].

In the present work, we have studied the effect of incorporating different types of ridges in the meander channels with a ratio of 1:2 to increase the mixing efficiency. The ridges are designed such that they protrude inward the walls of the microchannels. The fluid properties vary significantly as they move through the microchannel depending on the geometry. The design was optimized based on simulation studies and it was verified experimentally using coloured solutions.

2. Design and simulation studies

2.1. Design
The microfluidic design consisted of two inlets connected to a main flow channel with a T-joint. The length, width and height of the channel were set to be 29400 µm, 100 µm and 100 µm respectively. From our previous works, it has been shown that efficient mixing occurs in meander channels when compared to straight channels. It has also been proved that mixing efficiency is improved when we have the diameters of the channels varying alternatively. Hence, to further improve mixing in microfluidic channels, we have chosen the microfluidic mixing channel to be meander shaped having the cross-sectional diameter varying alternatively [15]. The mixing efficiency in the meander geometry can be improved further by incorporating ridges on the walls of the microchannels. Here, analysis has been carried out by incorporating three types of ridges on the walls of the microchannels up to the
fourth meander of the modified geometry, and the effect on mixing was studied in each case. Figure 1. shows the different designs analysed in this study. Figure 1.(a) shows a simple meander channel with alternating varying diameters with \( a = 200 \mu m \) and \( b = 400 \mu m \). Figure 1.(b), 1.(c) and 1.(d) show the meander channels modified with triangular, square and curved shaped ridges. The dimensions of the square shaped ridges are \( 40 \mu m \times 40 \mu m \). The curved ridges have a depth of \( 40 \mu m \) and a breadth of \( 40 \mu m \). The triangular shaped ridges have a height of \( 40 \mu m \) and a base length of \( 40 \mu m \).

The concentration profile in each of these three cases is compared and the mixing efficiency is calculated in each case.

2.2. Simulation studies
For the numerical analysis, 3D models of the proposed micromixers were created and their mixing efficiency was evaluated using COMSOL Multiphysics 4.3a. The flow pattern of fluids in the microfluidic channels were solved using the Laminar flow interface in the software. The extent of mixing between the two streams was studied using the Transport of Dilute Species Interface. The model input fluids, between which mixing is studied, was chosen to be ethanol and water. The boundary condition at the inlets was taken as laminar inflow at atmospheric pressure. The outlet has the pressure set to be zero static pressure. The flow was assumed to be incompressible and no slip boundary condition was set at the inner walls of the channels.

![Figure 1](image-url)
Single phase laminar flow physics is used for studying the velocity profile. The Navier-Stokes equation which governs the single phase flow is given by

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0$$  \hspace{1cm} (1)

The momentum equation is given by

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho (u \nabla) \mathbf{u} = \nabla p - \tau + \mathbf{F}$$  \hspace{1cm} (2)

Here $\rho$ is the density ($\text{kg/m}^3$), $\mathbf{u}$ is velocity vector, $p$ is pressure (P), $\tau$ is the viscous stress tensor (Pa) and $\mathbf{F}$ is the volume force vector (N/m$^3$).

The mixing efficiency which is obtained by solving the transport of the diluted species interface solves the convection diffusion model which uses the mass transfer equation to analyse the concentrations at different locations.

The mass balance equation is given by

$$\frac{\partial c}{\partial t} + u \nabla c = D \nabla^2 c + R$$  \hspace{1cm} (3)

Here, $c$ is the concentration of the species (mol/m$^3$); $D$ is the diffusion coefficient (m$^2$/s); $R$ is the reaction rate expression for the species (mol/(m$^3$.s)) and $u$ is the velocity vector (m/s).

In order to obtain the concentration profile, the geometry is modelled such that the concentration of species through one of the inlets was taken as 0 (indicated by blue color) and the concentration through the other inlet is taken as 1 (indicated by red color). Efficient mixing is indicated by the complete absence of red and blue color with the presence of green color at the outlet which indicates a concentration value of 0.5.

The extent of mixing is mathematically found out by calculating the standard deviation. The equation for standard deviation is given by

$$\sigma = \left[ \frac{1}{n} \sum_{i=1}^{n} C_i - \bar{C} \right]^{1/2}$$  \hspace{1cm} (4)

Here, $C_i$ is the concentration at the $i^{th}$ point and $\bar{C}$ is the average concentration along the sampled sections of the microchannel. Standard deviation should be close to 0 if homogenous mixing has taken place and if no mixing has taken place the value will tend towards 0.5.

### 3. Fabrication

The optimized design was fabricated using photolithography followed by soft lithography. Briefly, a 3-inch glass plate was washed with piranha solution followed by distilled water. After the plate was properly dried, negative photoresist SU-8 was spin-coated with a spin speed of 1000 rpm for 100 s followed by a spread speed of 1400 rpm for 10 s. After prebaking the plate at 120 °C for 30 minutes, direct laser write technology was used to pattern the design onto the glass plate. After post baking the substrate at a temperature of 95 °C for 30 minutes, the unexposed regions were removed by developing the substrate in a developer solution. The developed master is then used for soft lithography, in which, the base agent and the curing agent of PDMS is mixed well in the ratio 10:1 and poured on the surface of the substrate. Bubbles were removed with the help of a vacuum dessicator. This is followed by baking the substrate at a temperature of 100 °C for 30 minutes, after which the stamp can be peeled off from the master. The microscopic image of the fabricated microchannels is shown in figure 2.
4. Results and Discussion

4.1. Simulation results

The simulation results obtained by solving different 3D geometries provided the velocity profile in the microfluidic channels and the extent of mixing in each case. The velocity profile obtained in the microfluidic channels is shown in figure 3. It is observed that the fluid has maximum velocity at the centre of the microchannel and it decreased to zero as it approaches the walls of the microfluidic channels due to friction [24]. The frictional force between the walls of the microfluidic channels and the liquid layer just in contact with it is very high whereas it is low between fluid layers at the centre of the microchannel. Therefore, the fluid takes a parabolic flow profile within the microfluidic channel.

In order to study the mixing efficiency, the concentration profile across each of the meander channel was analysed. The design was optimized based on distance required for the geometry to attain complete uniform mixing. Two major factors contribute to mixing within the microfluidic channels, (i) residence time of fluids in the microchannel, (ii) chaotic advections induced in the microchannels due to their geometry [25]. When the residence time of fluids in the microchannel increases, the amount of time required for diffusion of molecules in the streams also increases. Since the flow through microfluidic channels has a very low Reynolds number and the flow is laminar, mixing is only by diffusion and is a slow process [17]. By inducing chaotic advections, the laminar flow is disturbed and the mixing enhanced. The incorporated ridges act as flow barriers are thus disturb the laminarity in the flow giving rising to chaotic advections thereby inducing turbulence. Therefore, mixing takes place at a much shorter time. The concentration plot obtained for different geometries analysed is shown in figure 4.
Figure 3. Velocity profile of the flow inside the microfluidic channel.

Figure 4. Concentration profile in the microfluidic geometries analysed.
Figure 5. Concentration distribution along the cross-sectional diameter at the end of the fourth meander channel.

The variation along the cross-section is further analysed by calculating the standard deviation of concentration along this line. Efficient and uniform mixing would yield a standard deviation close to zero. The standard deviation calculated for the different geometries are tabulated in Table 1.

Table 1. Standard deviation obtained from the cutline at the centre of the fourth meander channel.

| Type of geometry                              | Standard deviation (σ)   |
|----------------------------------------------|--------------------------|
| Meander geometry with no ridges              | 0.008870582              |
| Meander geometry with square shaped ridges   | 0.001244215              |
| Meander geometry with curved shaped ridges   | 0.002241901              |
| Meander geometry with triangular shaped ridges| 0.000898912              |

From figure 5, and the calculations of standard deviation[27] shown in table 1., it is found that the modified geometry with triangular ridges on the walls of the microchannels has the lowest value of standard deviation and the same shows very less variation in concentration in the fourth meander channel. Therefore it can be concluded that the meander geometry with triangular ridges is better compared to the other geometries. The dimension of the triangular ridges can be increased further to decrease the path of the fluid flow and thereby making the diffusion faster. Thus mixing efficiency can be increased by many folds in a modified meander channel with triangular ridges incorporated in them.

4.2. Experimental Evaluation
The optimized design was fabricated by photolithography [28] followed by soft lithography[29]. To understand the mixing efficiency two coloured fluids, as shown in figure 6., methyl orange (A) and
methylene blue (B) were chosen. When a drop of A and B were mixed, a greyish-green colour (C) was obtained.

![Figure 6. Mixing of two coloured fluids.](image)

Once the coloured liquids were loaded, negative pressure was applied using the syringe connected to the outlet. As the fluids flow through the microfluidic channel incorporated with triangular ridges, mixing occurs. Figure 7. shows the qualitative extent of mixing in the microfluidic channels. It was seen from the figure that we obtain a uniform greyish-green colour at the outlet just as expected thus proving the uniform mixing within the microfluidic channels.

![Figure 7. Mixing analysis in the microfluidic channel.](image)

5. Conclusion
In this work, we have analysed and optimized the performance of ridges incorporated meander shaped microchannels to enhance the mixing efficiency. Out of the triangular shaped, square shaped and smooth ridges, it was seen that enhanced mixing occurs in microfluidic channels incorporating triangular shaped ridges. The concentration distribution along each of the meander channels was evaluated using simulation studies. It was found that the geometry with triangular shaped ridges showed better mixing efficiency compared to square shaped and smooth ridges. Also, there was no dead volume accumulation in the triangular ridges incorporated microchannels when compare to square shaped and smooth ridges. The optimized design was fabricated using photolithography followed by soft lithography. Experimental studies were carried out using coloured solutions and the simulation studies were verified.
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