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Mixers and pumps for microfluidic devices, using conducting polymers

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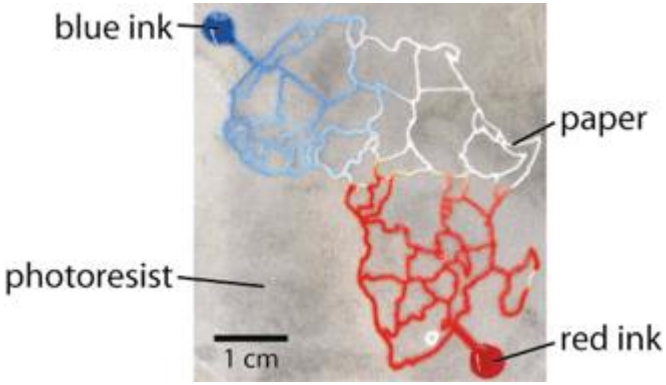
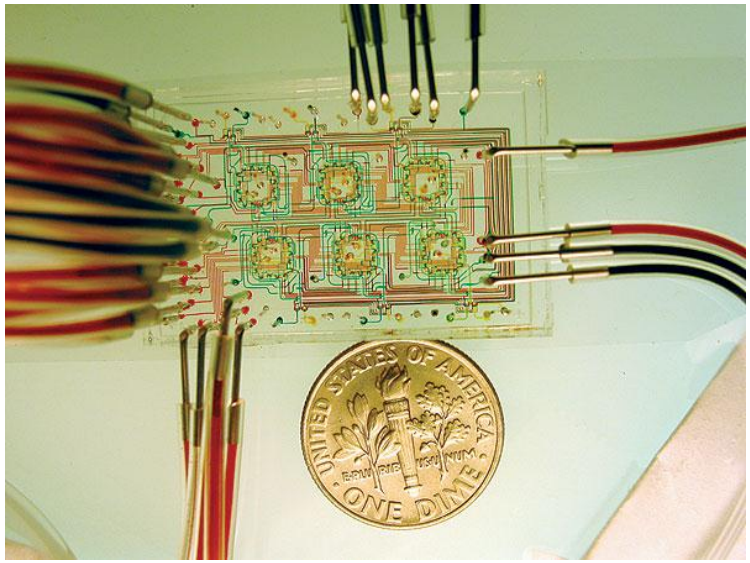
Microfluidics

- It is the science and technology of systems that process or manipulate small (10^{-9} to 10^{-18} litres) amounts of fluids, using channels with dimensions of tens to hundreds of micrometres.



- Microfluidic systems offers lot of advantages and has the potential to influence various fields such as medical diagnostics ,chemical synthesis, cell culture , optics and information technology. [1]

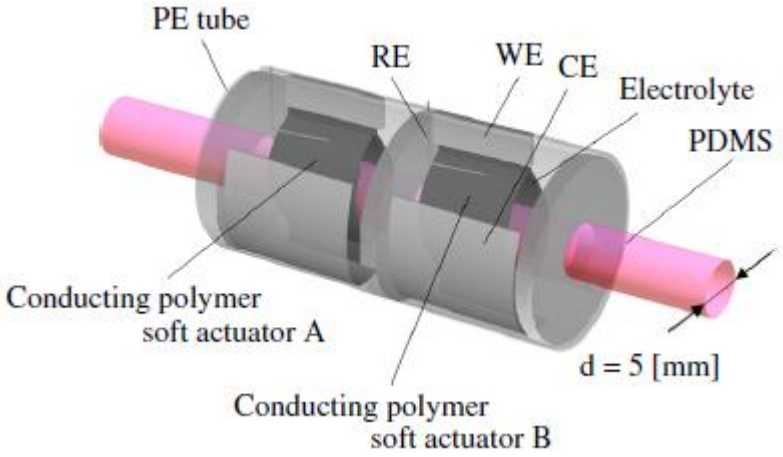
- Incorporating mixers and pumps into these systems is still a bottleneck in the fabrication process.

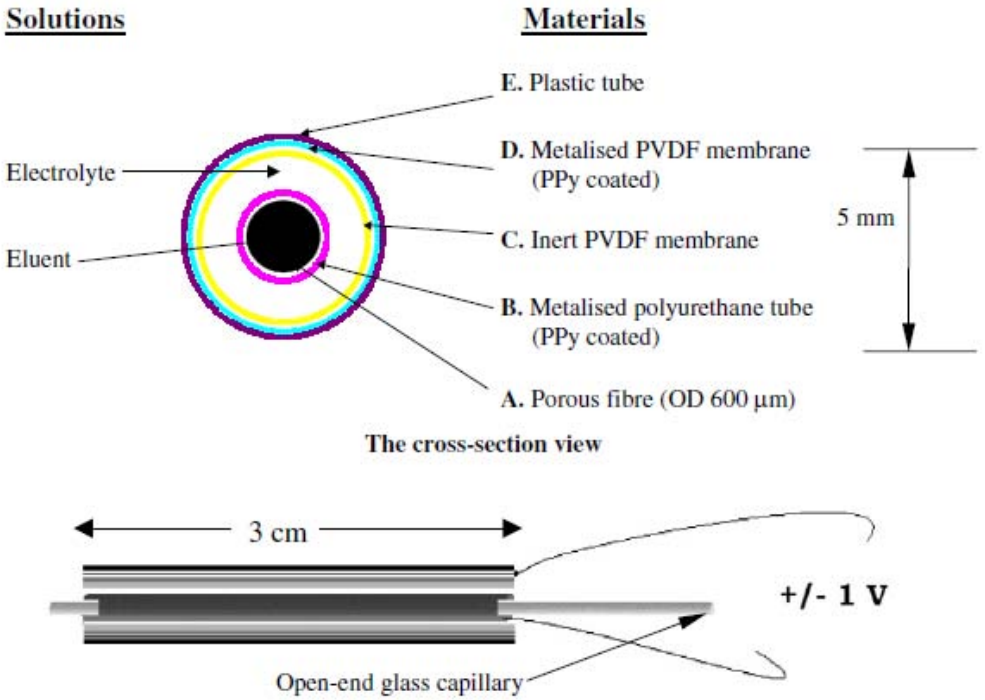


1.G.M. Whitesides, Nature-442(2006).
2 .A rapid method for prototyping paper-based microfluidic devices, George M. Whitesides et al, 2009.
3. Long-term monitoring of bacteria undergoing programmed population control in a microchemostat, Balagaddé, F. K et al 2005

Micropumps

Most of the existing micropumps and micromixers are difficult to include in microfluidic fabrication process

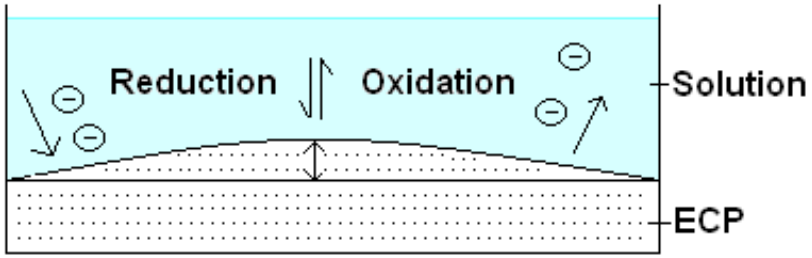




- Our aim is to design a micropump that's simple and will be easier to include in microfabrication steps.

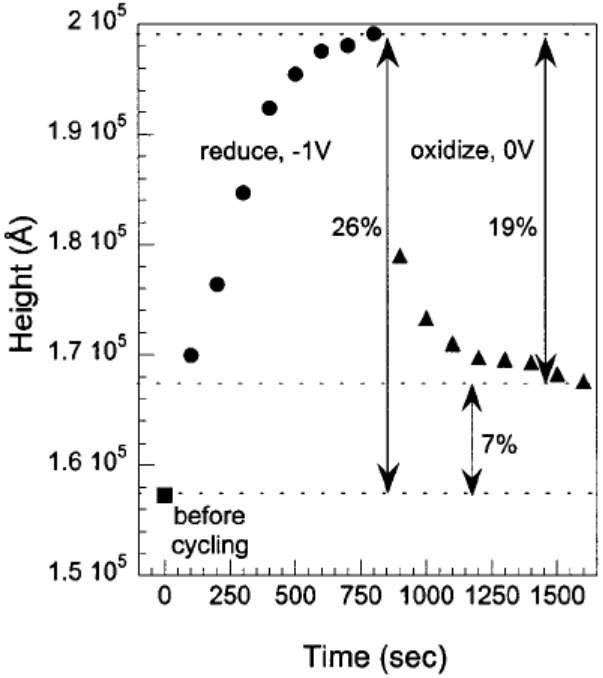
1. TITAN: a conducting polymer based microfluidic pump, Y Wu et al, 2005
2. A micropump driven by a polypyrrole-based conducting polymer soft actuator , Yoshitaka Naka et al,2009

Conducting polymers



$$Ppy + B^- \underset{k^-}{\overset{k^+}{\rightleftharpoons}} (Ppy^+B^-) + e^-$$

$(1-\varepsilon)$ (ε)

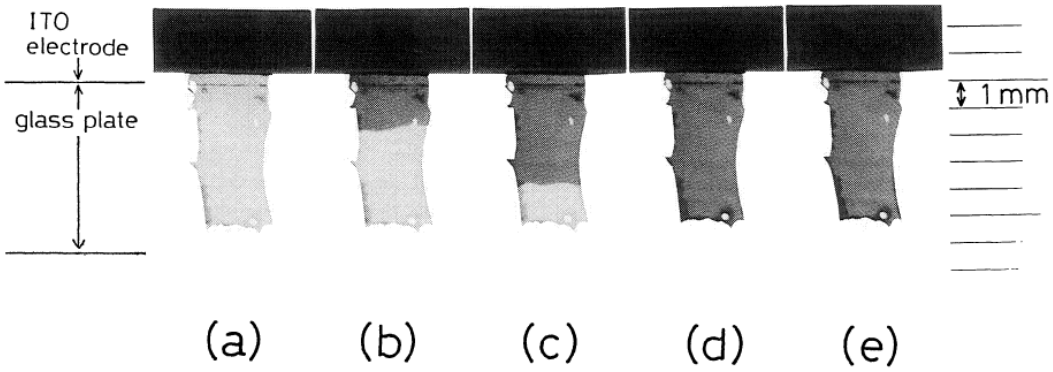


- When conducting polymers switch between oxidized and reduced state, the conductivity, color and volume undergo significant changes .
- This is due to the ion movement into and out of the polymer from the electrolyte.
- It has been reported that Polypyrrole undergoes up to 120% volume change .
- Thus CP's are attractive materials for inducing fluid movement in microchannels

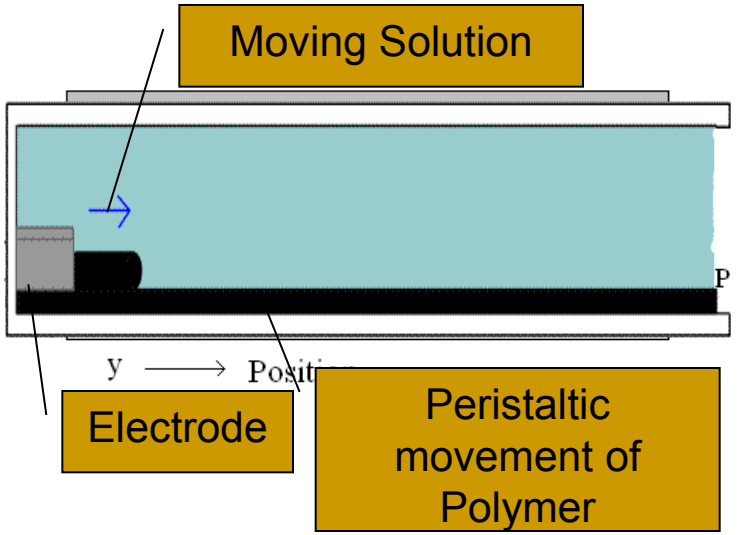
1. Volume Change in Polypyrrole Studied by Atomic Force Microscopy, Elisabeth Smela et al, 2001

Oxidation wave

- Tezuka et al. in 1991 reported an oxidation wave phenomenon in conducting polymers
- When anodic potential is applied to one end of a polymer strip, the oxidation process starts from that end and propagates as a wave.
- This oxidation wave will be coupled with a mechanical deformation.

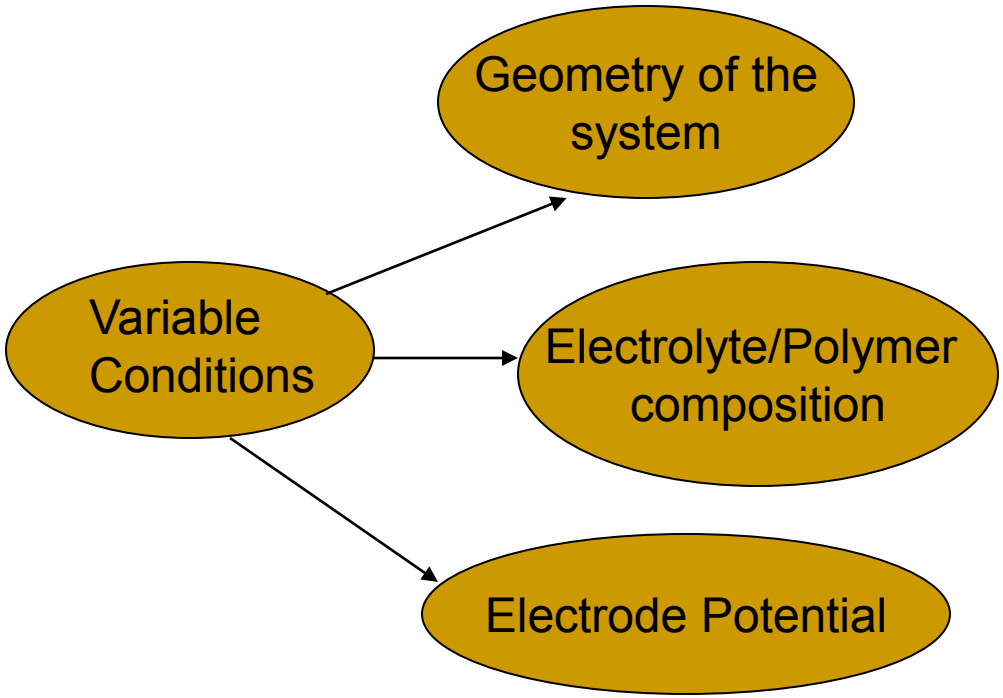


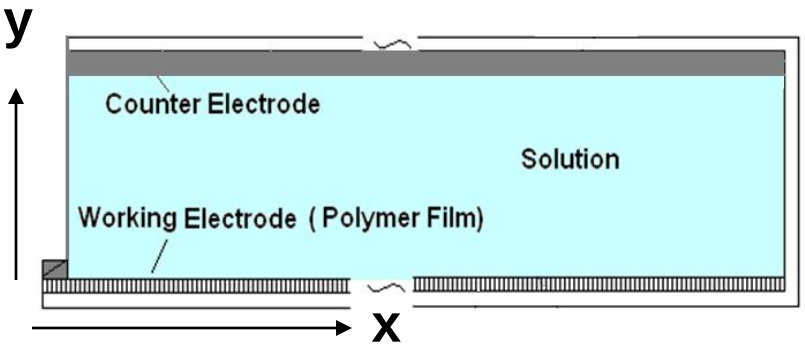
Time-sequence photographs of a polypyrrole film at t=0 (a), 1.6 (b), 3.2 (c), 4.8 (d), 9.6 (e) s.



1. *Observation of propagation speed of conductive front in electrochemical doping process of polypyrrole films,* Yoshihiko Tezuka et al , *1991*

Modeling the oxidation wave in CP

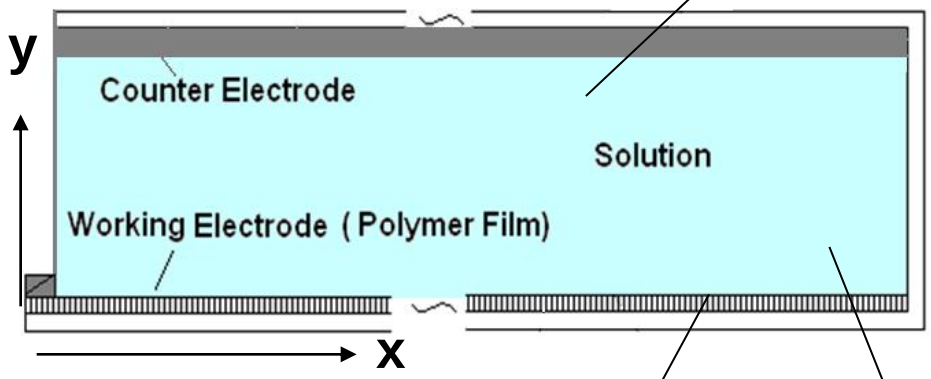




$$\phi_P \equiv \phi_P(x,t)$$
$$\varepsilon \equiv \varepsilon(x,t)$$
$$\phi_S \equiv \phi_S(x,y,t)$$
$$C \equiv C(x,y,t)$$

- Determine under what conditions electrically-stimulated mechanical surface waves can be triggered at ECP- electrolyte interface

Equations involved



In solution

$$\frac{\partial C}{\partial t} = D_A \nabla^2 C + U_A \nabla \cdot (C \nabla \phi_S)$$

$$[U_A - U_B]\frac{RT}{F} F\left(\nabla^2 C\right) + [U_A + U_B] F \nabla \cdot \left(C \nabla \phi_s\right) = 0$$

In Polymer

$$\frac{\partial \phi_p}{\partial x} = -\left(\frac{\rho}{w \Delta y}\right) I_p$$

$$\frac{\partial I_p}{\partial x} = -I_s \frac{w}{A}$$

$$I_s = -J_B F$$

$$\sigma_p = \frac{\sigma_{\max} - \sigma_{\min}}{1 + e^{(\varepsilon - \varepsilon t)/tw}} + \sigma_{\min}$$

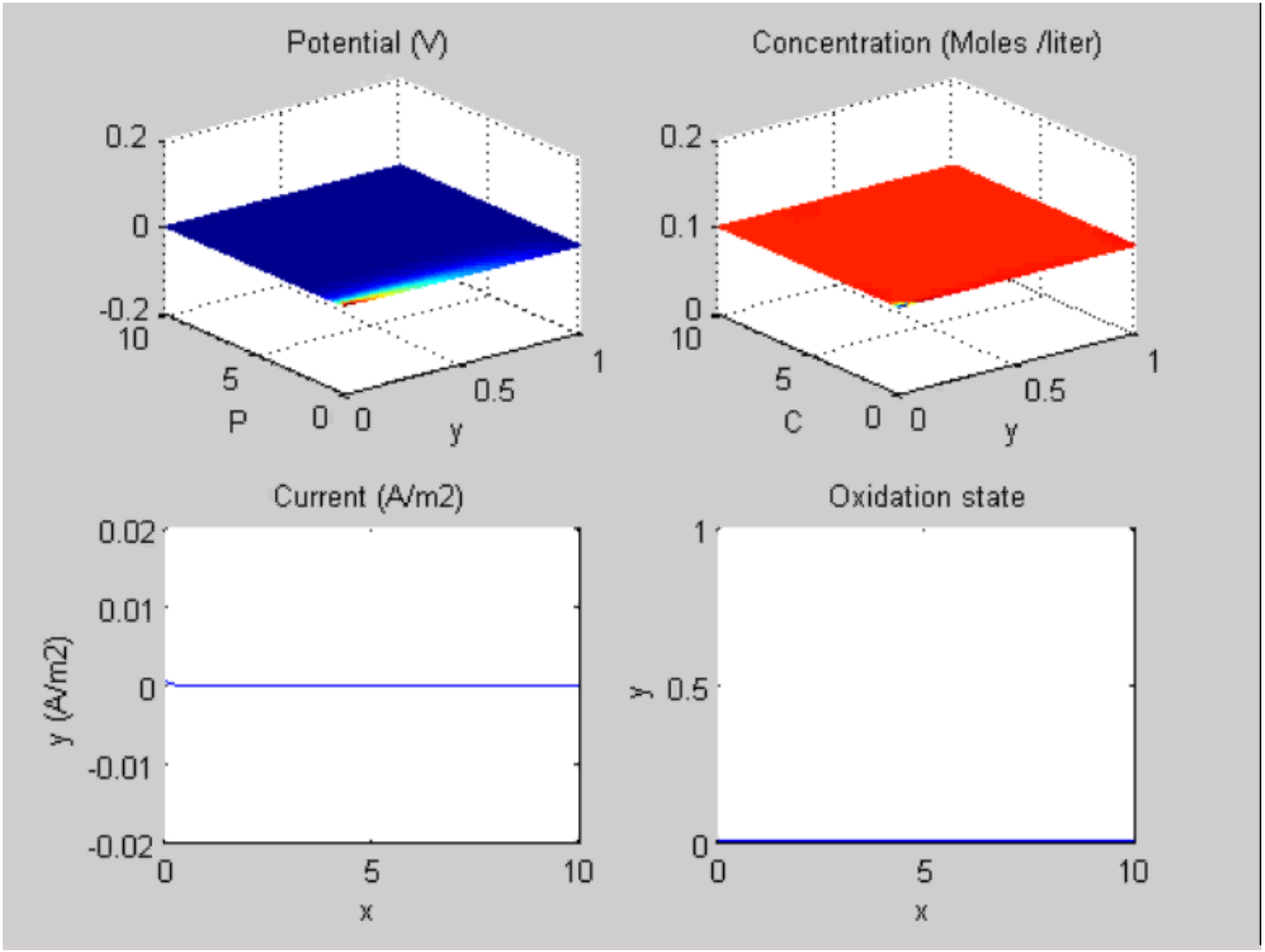
At Solution-Polymer Interface

$$\phi_p - \phi_s = \Delta\phi^{01} - \frac{RT}{F} \ln\left(\frac{C_B(1-\varepsilon)}{C_0 \varepsilon}\right)$$

$$M \cdot \Delta y \cdot \frac{\partial \varepsilon}{\partial t} = -\left(U_B \frac{RT}{F} \frac{\partial C_B}{\partial y} - U_B C_B \frac{\partial \phi_s}{\partial y}\right)$$

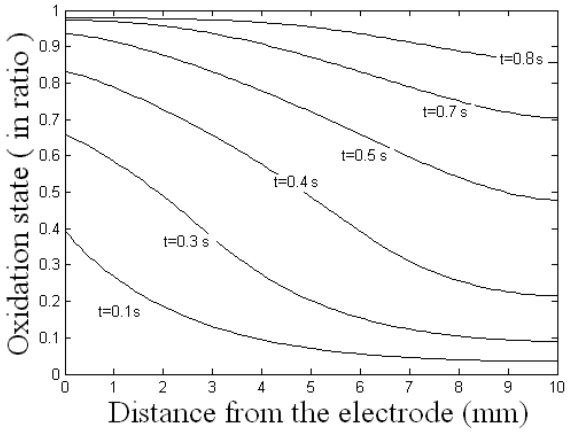
$$J_A = -\left(U_A \frac{RT}{F} \frac{\partial C_A}{\partial y} + U_A C_A \frac{\partial \phi_s}{\partial y}\right) = 0$$

Oxidation wave modelling -results

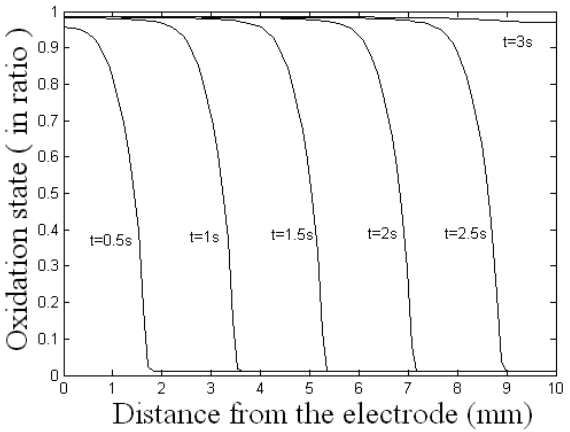


Oxidation wave modelling -results

The property of the propagating oxidation wave can be modified by varying the conductivity ratios

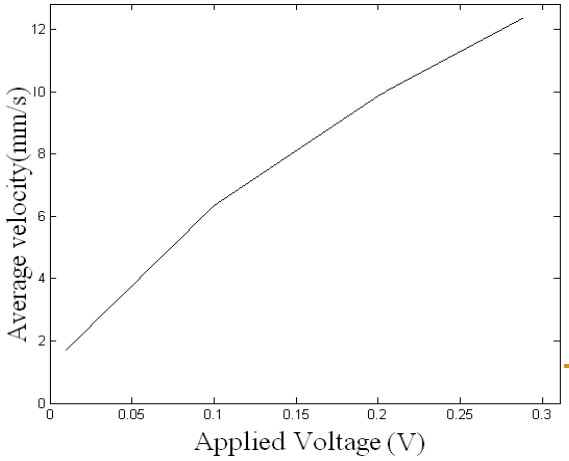


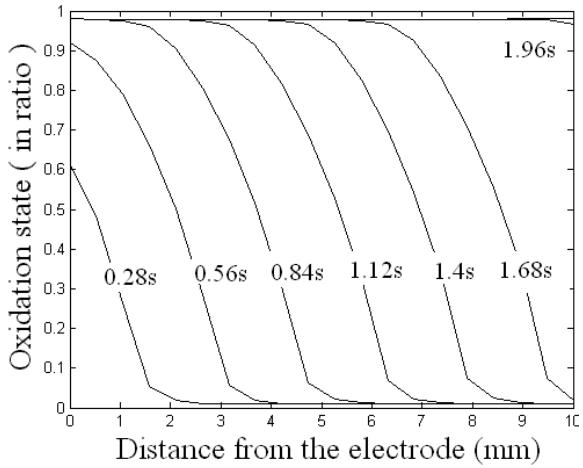
a) $\frac{\text{Eletrolyte conductivity}}{\text{Minimum Polymer conductivity}} = 0.001$



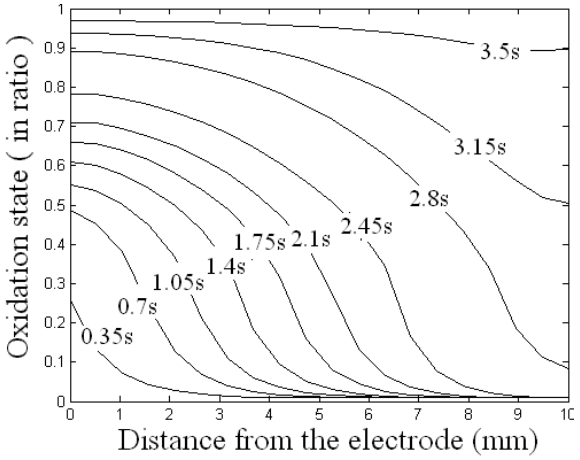
b) $\frac{\text{Eletrolyte conductivity}}{\text{Minimum Polymer conductivity}} = 1$

The wave velocity increases with applied voltage





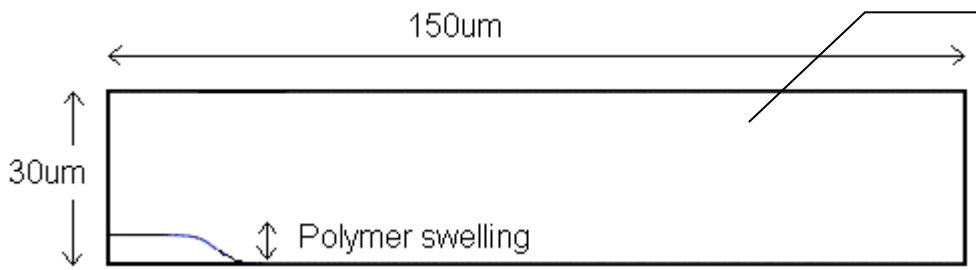
b) Distance between electrodes = 1 mm



a) Distance between electrodes = 5 mm

When distance between polymer and counter electrode is increased, the rate of the oxidation is reduced and the wave propagates slowly and also the wave shape changes

Design of mixer and pump

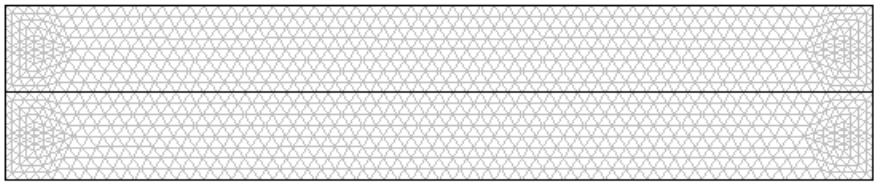


Navier stokes equation

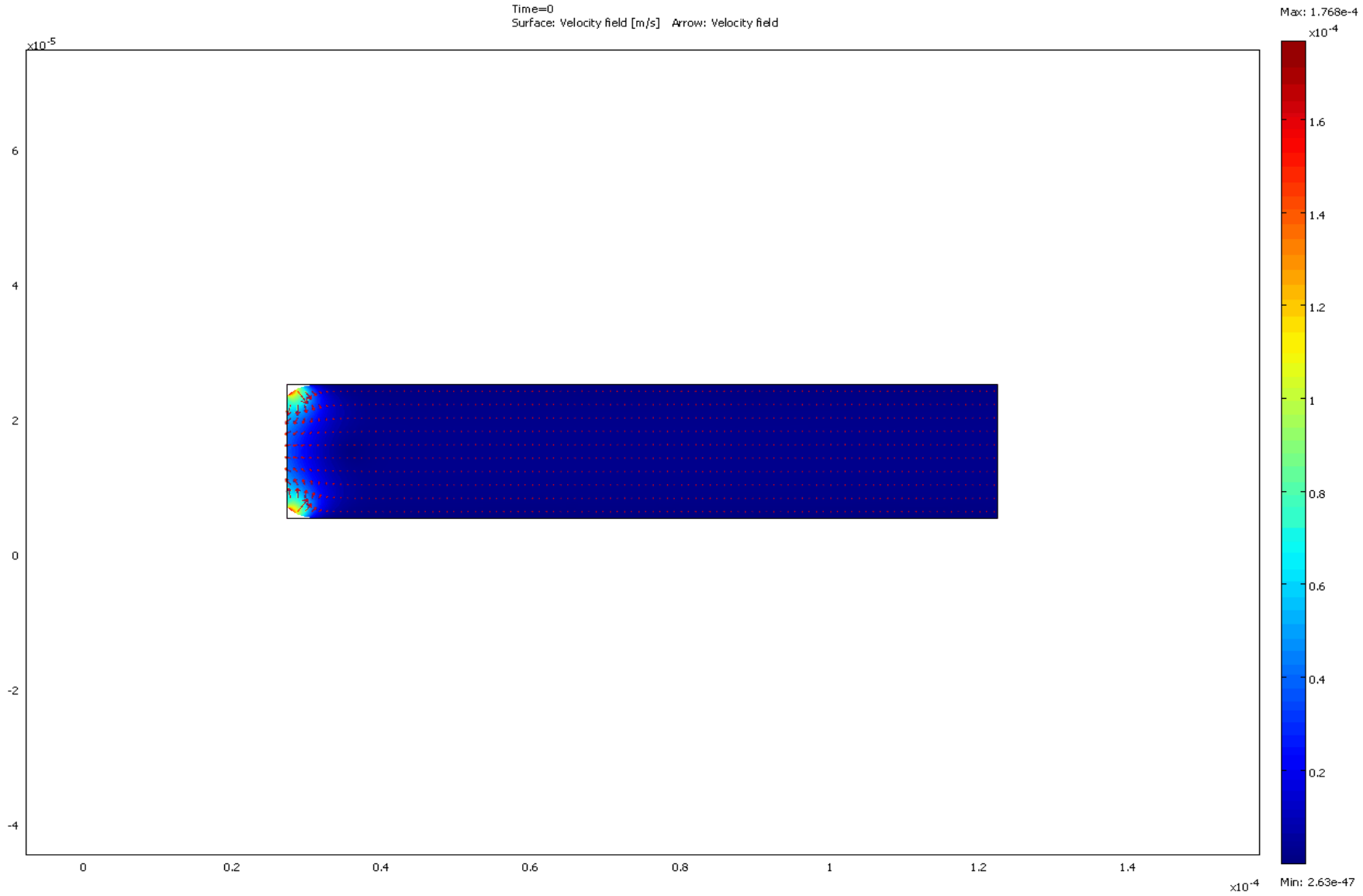
- To determine the fluid velocity due to mechanical deformation incompressible Navier-stokes equation was solved
- Comsol mutiphysics finite element solver was used to solve the equations
- Moving mesh [ALE] was used to move the boundary to simulate the oxidation wave.

Moving mesh [ALE]

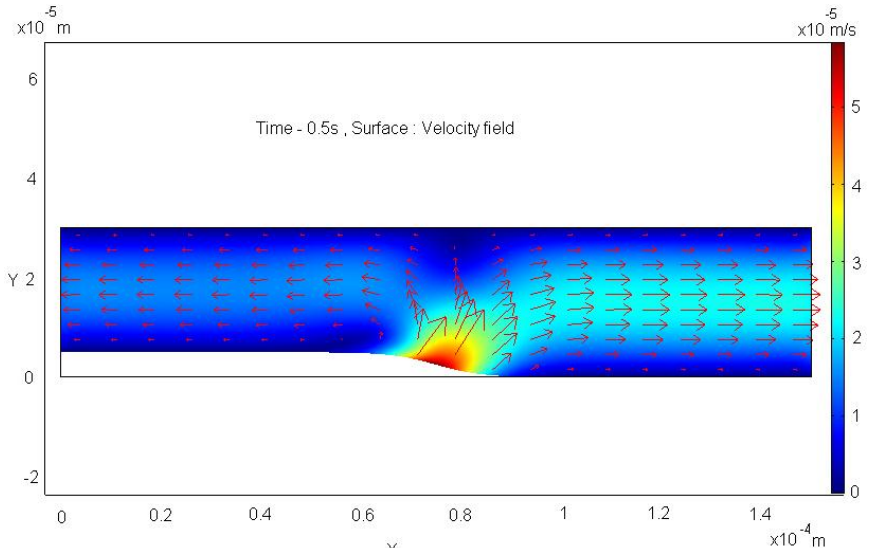
$$y(x,t) = A - \frac{A}{1+e^{(x-V*t)/S}}$$

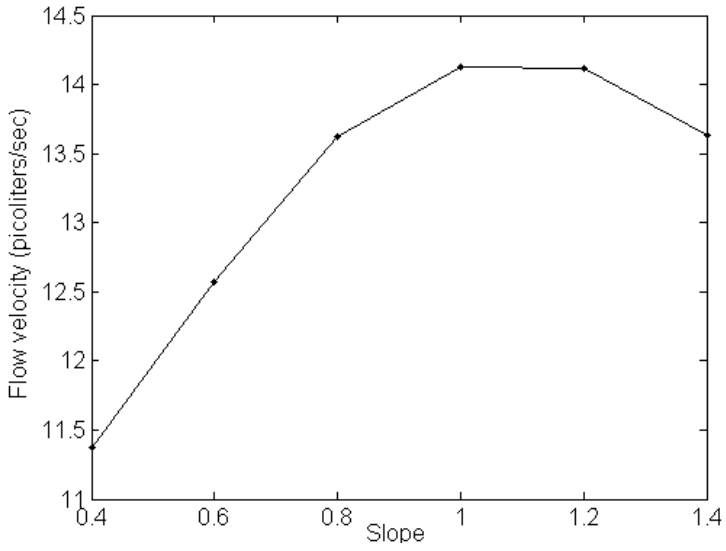


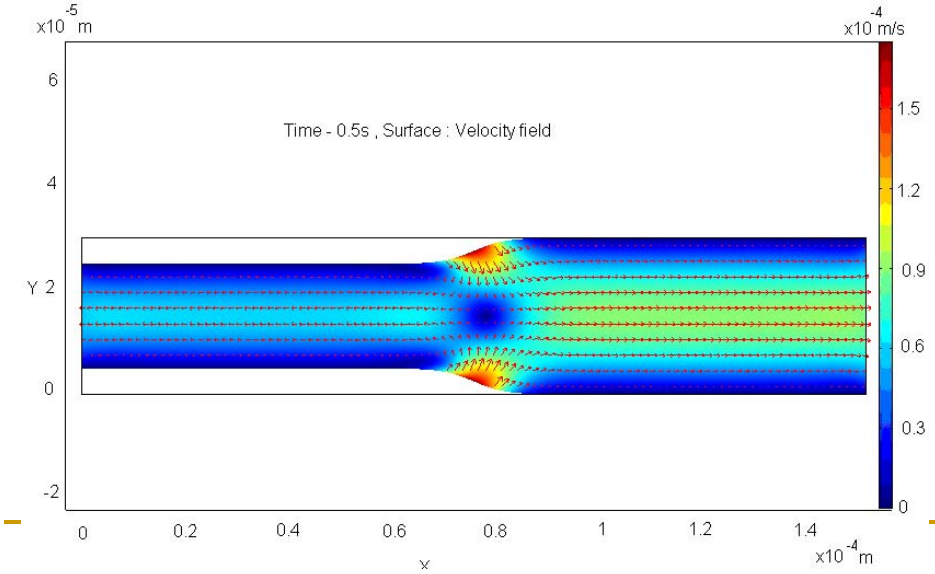
Micropump

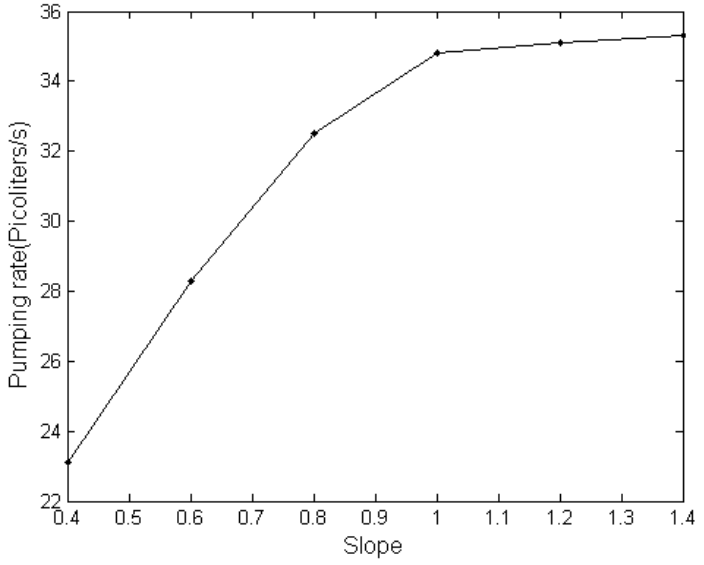

Time=0
Surface: Velocity field [m/s] Arrow: Velocity field
x10-5
6
4
2
0
-2
-4
0
0.2
0.4
0.6
0.8
1
1.2
1.4
x10-4
Max: 1.768e-4
x10-4
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
Min: 2.63e-47

Design of a micro-pump

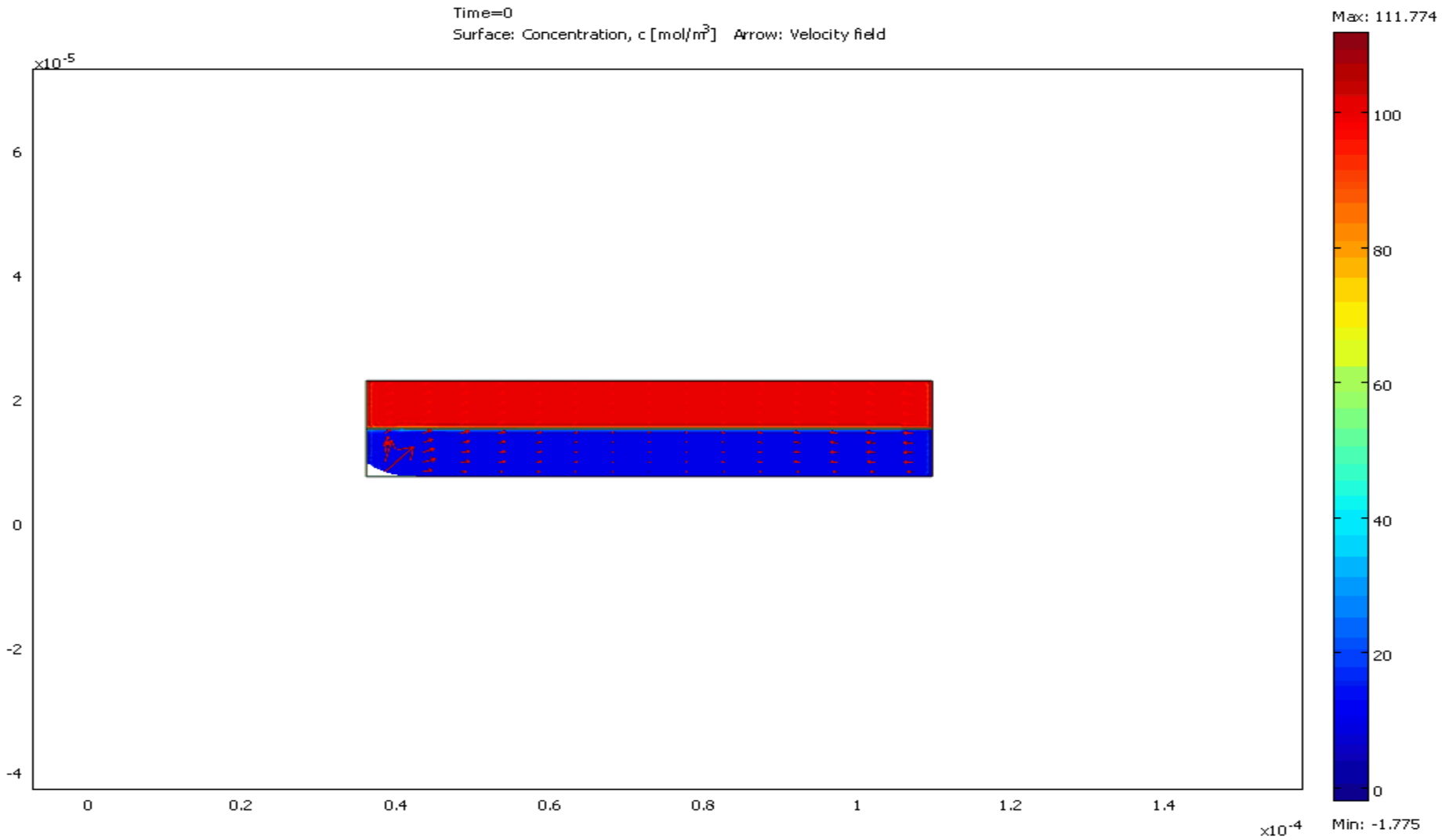




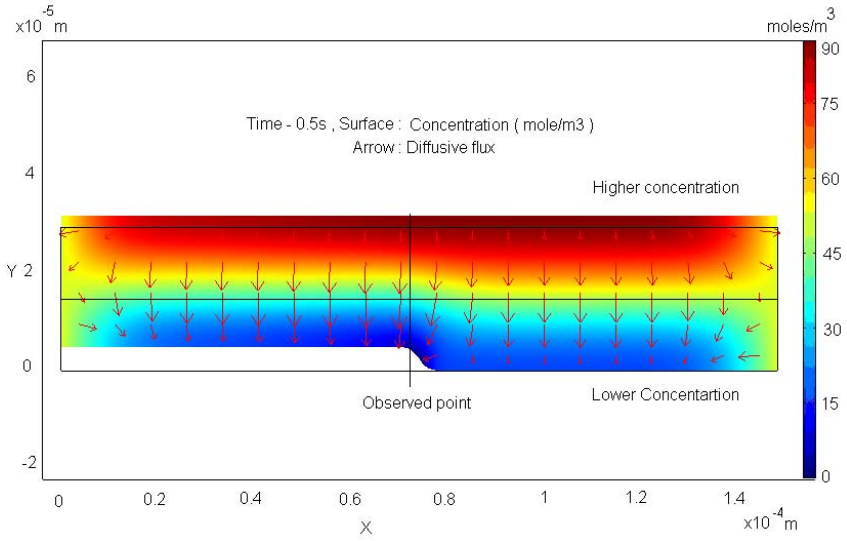


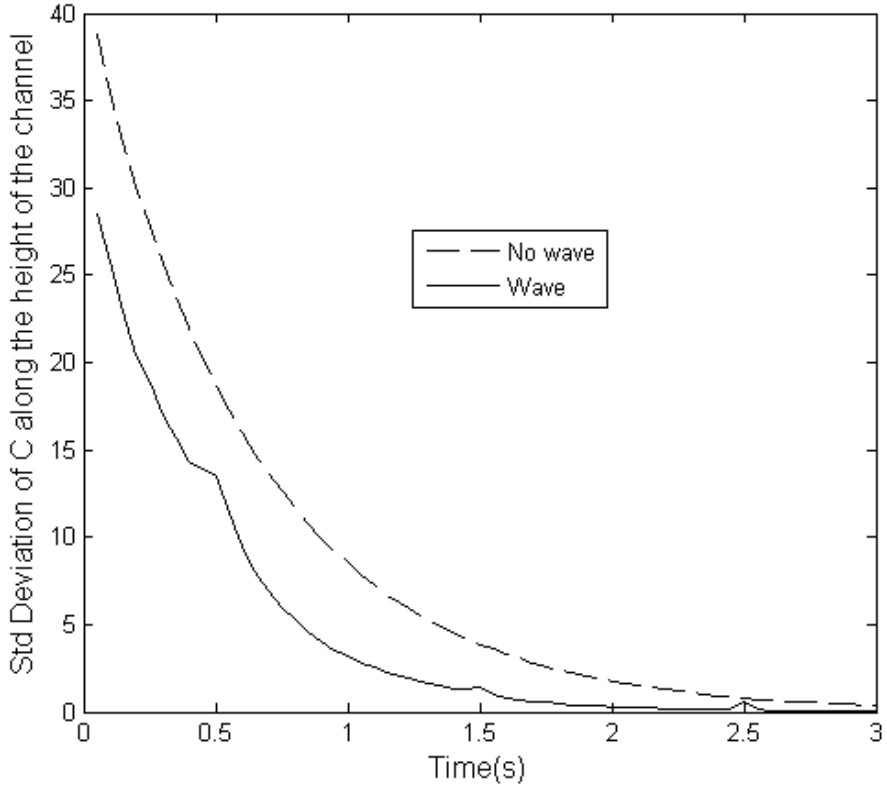


Micro-mixer design



Design of a micro-mixer



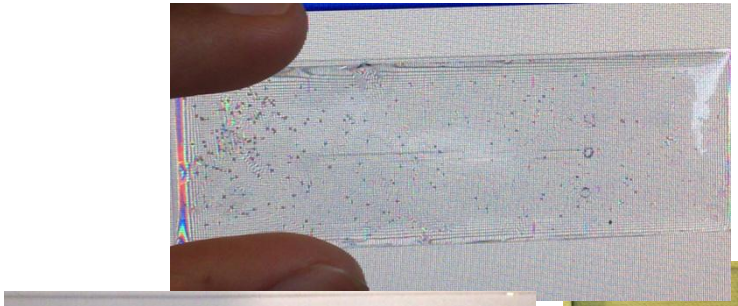


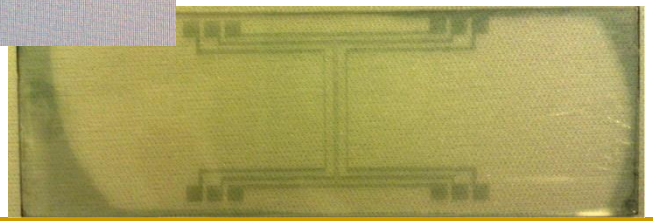
Summary

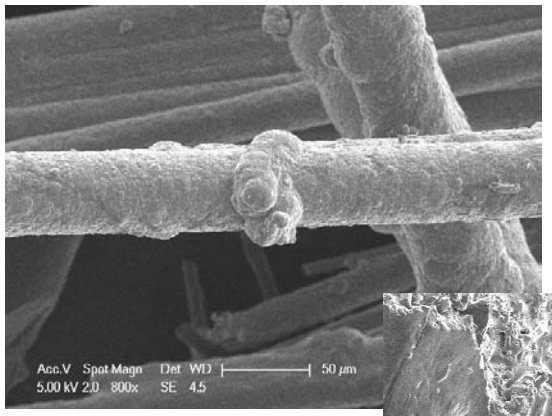
- A propagating wave of deformation of an electrochemically-active conducting polymer can be launched along a polymer strip as a consequence of the electrochemical reaction.
- The shape of the wave front and its velocity depend upon the relative conductivities of the electrolyte and of the polymer in its oxidised and reduced states.
- A micro-pump and a micro-mixer can be designed that utilises this phenomenon

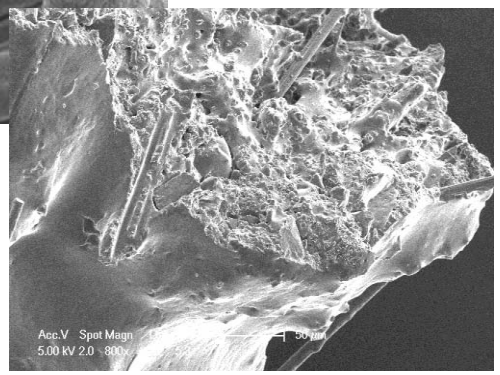
Future Work

- Experimental verification of the model.
- Build a working device !!!.









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Thank you