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Design and fabrication of microfluidic actuators towards microanalysis systems for bioaffinity assays

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ABSTRACT

This work focuses on the realization of three different micro-actuators that will be integrated in a lab-on-chip for bioaffinity assays. The aim is to create a microfluidic network to control the sample and reagent delivery as well as the washing cycles for a complete analysis. The three micropumps have different working principles (electromagnetic, electrolytic and peristaltic actuation methods), but they share the same fabrication process. The reason for adopting three different actuation modes is mainly related to the different functionalities that have to be managed at microfluidic level. In particular the electrolytic one-shot micropump will be used for sample and reagents delivery, while the peristaltic and the electromagnetic micropumps are both good candidates for the washing cycles.

1. Introduction

Microfluidics is a field that provides tools and concepts for elaborating complex lab-on-a-chip devices. The integration of actuators on the chip is a crucial issue, since it is difficult to control many independent fluid channels by a few external devices. In this work, three different kinds of microfluidic actuators were designed and fabricated. The actuator modules are a peristaltic micropump, an electromagnetic micropump and an electrolytic micropump. The micro-actuators were designed to be combined in one lab-on-chip, as in Fig. 1, to provide the entire fluidic control for biological tests in bioaffinity assays [1]. The reason for adopting three different actuation modes is mainly related to the different functionalities that have to be managed at microfluidic level. In particular the electrolytic one-shot micropump will be used for sample and reagents delivery, while the peristaltic and the electromagnetic micropumps are both good candidates for the washing cycles.

Many types of micropumps have been investigated since early 1990s [2]. With respect to the state of the art, the effort of this work focused on the realization of different kinds of micro-actuators that can be integrated in a final lab-on-chip. To this scope, the micropumps should be fabricated using compatible fabrication processes and should provide a large range of flow rates to satisfy the applications requirements. In this particular work, the micropumps was designed to obtain flow rates spanning from the 1 μL/min of the peristaltic micropump to the expected 100 μL/min of the electrolytic micropump. The estimated flow rate for the electromagnetic micropump is 10 μL/min.

2. Design of micropumps

2.1. Peristaltic micropump

The peristaltic micropump is composed of a sequence of pneumatic valves. Valves are formed at the intersection between a fluidic channel and a control channel located in two separate layers: a control layer and a fluidic layer. When pressure is increased in the control channel (e.g., injecting air or water) the membrane separating the two channels deflects and closes the fluidic channel, thus blocking the flow inside. Assembling three valves in series, one can fabricate peristaltic pumps [3].

The micropump was designed to obtain a flow rate of about 1 μL/min. The control layer is composed of three 400 μm channels equally spaced by 1 mm. The width of the single channel of the fluidic layer was varied ranging between 200 μm and 1 mm in order to find the best configuration for the flow rate optimization. The height of the fluidic channels was changed accordingly, in order to maintain the ratio 1:10 between height and width, that avoids the collapse of the channel under the applied pressure. The control channels, instead, are 40 μm high and the PDMS membrane thickness is 30 μm.

2.2. Electrolytic micropump

The electrolytic micropump is an active actuation system without mechanical parts. The pumping pressure is given by the

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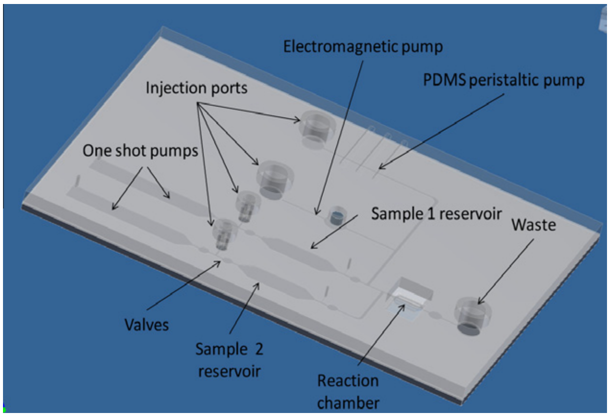

Fig. 1. Schematic view of the integrated microanalysis system for bioaffinity assays.

expansion of a gas bubble generated by hydrolysis. When an electric current passes through the water, it decomposes according to the following equations:

$$\text{Cathode (reduction)}: 2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^-(aq)$$
$$\text{Anode (oxidation)}: 4OH^-(aq) \rightarrow O_2(g) + 2H_2O(l) + 4e^-$$

The Nerst potential for this reaction is 1.23 V.

The bubble expansion rate and, consequently, the flow rate depend on the imposed current [4].

If platinum interdigitated electrodes are used, the current is calculated as follows:

$$i(t) = E_0\left(\frac{R_2}{R_2(R_1+R_2)}e^{-\frac{t}{\tau}}\right) + \frac{E_0}{R_1+R_2} \quad (1)$$

$$\tau = \frac{R_1R_2C}{(R_1+R_2)} \quad (2)$$

In Eqs. (1) and (2) E_0 is the Nernst potential, R_1 is the liquid resistance, R_2 is the polarization resistance and C is the double layer capacitance. R_1 is calculated from the cell constant C_k and the liquid conductivity ρ according to [4]:

$$R_1 = \frac{C_k}{\rho} \quad (3)$$

$$C_k = \frac{2}{NL} \quad (4)$$

N is the number of the interdigitated electrodes and L is the electrodes length.

Using deionized water and two interdigitated platinum electrodes 7 mm long (C_k = 47/m) it is possible to obtain a flow rate larger than 100 μL/min with a power consumption of about 300 mW.

3. Electromagnetic micropump

The electromagnetic micropump is based on the deformation of a membrane, due to the magnetic force between a permanent magnet and current carrying planar coil. The micropump is composed of a membrane, a pumping chamber and couple of Tesla valves for flow rectification. A Tesla valve has a bifurcated channel that re-enters the main flow channel perpendicularly when the flow is in the reverse direction, thus decreasing the net flow in that direction. The final result is a good one way directionality and low pressure losses [5].

The normal magnetic field at a distance x from the magnet is [6]

$$B_z(x) = \frac{B_r}{2}\left(\frac{l_m + x}{\sqrt{r^2 + (l_m + x)^2}} - \frac{x}{\sqrt{r^2 + x^2}}\right) \quad (5)$$

where B_r is the residual magnetization, l_m is the magnet thickness and r is the magnet radius.

For example, at a distance of 300 μm, the normal component of the magnetic field is 0.38 T, using a NdFeB magnet with a radius of 1 mm, a thickness of 2 mm and a residual magnetization of 1.29 T. The normal component of the electromagnetic force acting on a current carrying coil immersed in the magnet field is:

$$F_z = mB_z = NliB_z \quad (6)$$

In the previous formula, N is number of coil's turns, l is the coil length and i is the current.

The pumping flow rate can be written as the product among the stroke's volume, the frequency of the stroke and a parameter related to the valve efficiency

$$\text{Flow} = \text{Volume} \times \text{Frequency} \times \text{efficiency} \quad (7)$$

The valve efficiency is defined as:

$$E = \frac{|\phi_{\text{forward}} - \phi_{\text{backward}}|}{\phi_{\text{forward}}} \quad (8)$$

where ϕ is the flow rate in the forward and backward direction.

Considering a flow rate of 10 μL/min, an operative frequency of 20 Hz and an efficiency of 0.65 [7], the volume stroke is 0.32 μL that corresponds to a required membrane deflection of 22 μm for a membrane radius of 2 mm, 100 μm thick.

The Tesla valves introduce a pressure drop that can be considered constant in the pump chamber.

Using the electric analogy and the theoretical model reported in [8,9], the pressure drop can be estimated being about 22 KPa for a flow rate of 10 μL/min.

ANSYS (Ansys Inc., Canonsburg, PA, USA) simulation showed that considering a PDMS membrane 400 μm thick, a deflection of 22 μm corresponds to a pressure difference of 7.2 Pa; so the total pressure to apply to the membrane is 22 KPa plus 7.2 Pa at a frequency of 20 Hz.

This means the electromagnetic force required to deflect the membrane should be 370 mN. A possible solution for the design of the planar coil is: aluminum coil (square resistance 0.01 Ω) with 70 turns and a pace of 40 μm for a total length of 0.6 m. For an applied voltage of 10 V, the estimated current is 19 mA, with a power consumption of 190 mW.

4. Micropump fabrication and testing

4.1. Fabrication process

The fabrication process for the three micro-actuators is divided in two separated steps: the fluidic and control channels were realized using soft-lithography techniques, while the hard substrate with electrodes and electric connections were micromachined with conventional MEMS technologies.

For this second part, the process started with a 4-in. silicon wafer covered with a multilayer of dielectric for a good insulation (300 nm of grown silicon dioxide, 100 nm of LPCVD, 300 nm of TEOS). Negative photoresist was then spun on the wafer and patterned using photolithography technique in order to define the heater and thermometer for the following lift-off step. The wafer was inserted in e-gun evaporator (ULVAC EBX-16C) and a layer of chromium/platinum (5/150 nm) was evaporated on the surface. The unexposed photoresist was removed using acetone in ultrasonic bath and the Cr/Pt was sintered at 500 °C for 1 h. The platinum wires were insulated using the same multilayer described above and contacts were open to define the pads and the electrodes for the electrolytic micropumps. A thick layer (1.5 μm) of aluminum was then evaporated and patterned using lift-off