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Electronic Supplementary Information 1 (ESI 1)

Numerical simulation

Because the liquid-metal based EOF pump has a micro PDMS gap between the electrodes and the pumping channel, the electric field strength along the pumping channel wall cannot be determined directly. For better understanding how the EOF pump works, numerical simulation of the electric field distribution in the pumping channel was performed in this section. The simulation aims to investigate the effects of PDMS gap and pumping channel dimensions on the electric field distribution in the pumping channel, which is also very helpful for us to design this EOF pump. The commercial software Multiphysics COMSOL 3.5 was used to perform the simulation in this research.

Physical model and numerical method

Figure 1 shows the physical model of the liquid-metal based EOF pump in the simulation. Three parameters were considered in this study, including the PDMS gap (ranging from 0 μm to 200 μm), the pumping channel length (1 cm, 5 mm, 1 mm, 500 μm and 100 μm) and the pumping channel width (ranging from 5 μm to 80 μm), as shown in Fig. 4. All microchannels are 50 μm high. The electrode channels are 200 μm wide. The injection inlets and outlets of electrode channels are 5 mm away from the pumping channel. The distance between the injection inlet and outlet along the pumping channel is 1.1 cm. The electrode part close to the pumping channel is 1 mm long along the pumping channel.

In this EOF pump, the electroosmotic flow velocity at the solid-liquid interface of the pumping channel can be written as,

$$U_{wall} = \mu_{eo} E \qquad (1)$$

where E is the electric field strength along the pumping channel wall and μ_{eo} is the fluid electroosmotic mobility. The electroosmotic mobility (μ_{eo}) is a physical property parameter, which is only dependent on the types of fluid and channel wall, temperature, PH and ion concentration in fluid.[46-51] When DI water is used as working fluid in the PDMS pumping channel at room temperature, the electroosmotic mobility (μ_{eo}) is constant. Then the electroosmotic flow velocity can be determined by the electric field strength (*E*) along the pumping channel wall. Thus, the electric field strength (*E*) is the only factor for the pumping performance of this EOF pump.

In PDMS microfluidic channels, the electric potential ($\vec{\psi}$) can be described using the Poisson equation.

$$\nabla^2 \vec{\psi} = -\frac{\rho}{\varepsilon_0 \varepsilon_r} \qquad (2)$$

where ρ is the local free charge density in the medium, ε_0 and ε_r are the dielectric constant in the vacuum and the relative dielectric constant in the medium (PDMS ε_r=2.8 at 20 ℃;[43] DI water ε_r=80). In most electroosmosis applications, the electrical double layer has very small zeta potential as compared to externally applied electric potential. Meanwhile, the thickness of the electrical double layer (order of several nanometres) is extremely thin as compared to the channel dimension, which can be considered to be negligible. Under these considerations, in EOF pumps using electrically neutral aqueous solutions as pumping fluids (such as DI water) and insulation polymers (such as PDMS) as chip channels, the local free charge density can be considered to be zero, $\rho \approx 0$.[46]

Thus, the Poisson equation becomes the Laplace equation $\nabla^2 \vec{\psi} = 0$. The boundary condition $\partial\vec{\psi}/\partial n\big|_{wall} = 0$ is applied to each wall of the chip. The "n" term represents the electric potential gradient along the normal direction at the surface of the chip wall.

Numerical results

Figure 7 (ESI) shows the numerical results of the electric field (horizontal plane at the middle of the channel) of the EOF pump from the numerical model. The chip has a 40 μm wide, 1 cm long pumping channel. The PDMS gap between the electrodes and the pumping channel is 40 μm. A voltage of 50 V is applied at the liquid electrodes. As shown in Fig. 7 (ESI), the ohm-shape electrodes generate an electric field parallel to the pumping channel. Because of the long arms of the liquid electrodes, the electric field generated along the pumping channel between the electrodes is almost uniform and, which is ideal to form the electroosmotic flow in the pumping channel.

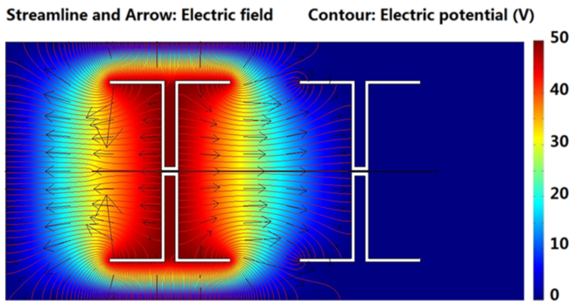

Fig. 7 (ESI) Electric field (horizontal plane at the middle of the channel) of EOF pump from numerical model

The PDMS gap between the electrodes and the pumping channel is a dominant factor of the electric field along the pumping channel wall. Due to the presence of the dielectric

PDMS between the electrodes and the pumping channel, the electric potential field in the pumping channel will be weakened. Figure 8 (ESI) shows the electric field along the pumping channel wall (side wall) as a function of PDMS gap. The pumping channel is 40 μm wide and 1 cm long. The applied voltage is 50 V. As shown in Fig. 8 (ESI), the electric field strength along the pumping channel wall largely decreases with the increasing of the PDMS gap. To obtain high electric field along the pumping channel wall, the PDMS gap should be as small as possible, if the breakdown of the PDMS gap under high voltage is not considered.

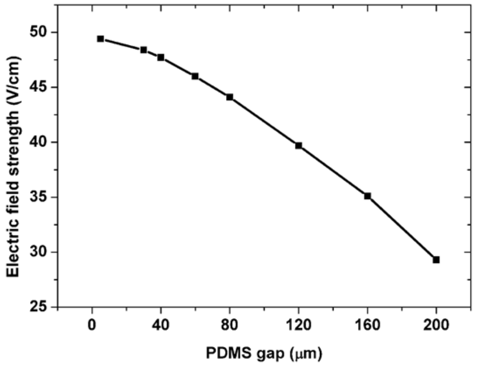

Fig. 8 (ESI) Electric field strength along pumping channel wall as a function of PDMS gap

The pumping channel width is also a key factor of the electric field along the pumping channel wall, especially for the dielectric working fluid. Figure 9 (ESI) shows the electric field along the pumping channel wall (side wall) as a function of pumping channel width. The pumping channel length is 1 cm. The applied voltage is 50 V. As shown in Fig. 9 (ESI), the electric field strength along the pumping channel wall will decrease dramatically when the pumping channel width increases from 5 μm to 80 μm. To reach the largest electric field strength in the pumping channel, the pumping channel should be as narrow as possible. In this work, the pumping channel width is suggested to be same with the PDMS gap (20~40 μm).

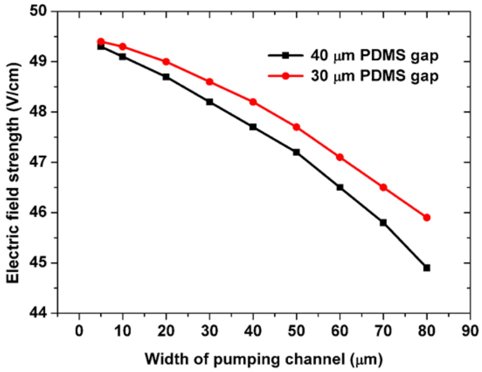

Fig. 9 (ESI) Electric field strength along pumping channel wall as a function of pumping channel width

Figure 10 (ESI) shows the electric field strength along the pumping channel wall (side wall) as a function of pumping length. The pumping channel is 40 μm wide. 30 μm and 40 μm PDMS gaps are considered. With a certain voltage of 50 V applied on the pumping channel, the electric field strength along the pumping channel wall decreases with the increasing of the pumping channel length. The electric field strength drops greatly when the pumping channel increases within the range of 0~2 mm. To obtain high electric strength, the pumping channel should be short while the PDMS gap between the electrodes and the pumping channel should be as small as possible. In this work, the pumping channel length is suggested to be 0~2 mm to increase the efficiency of applied voltage, while the PDMS gap is 20~40 μm.

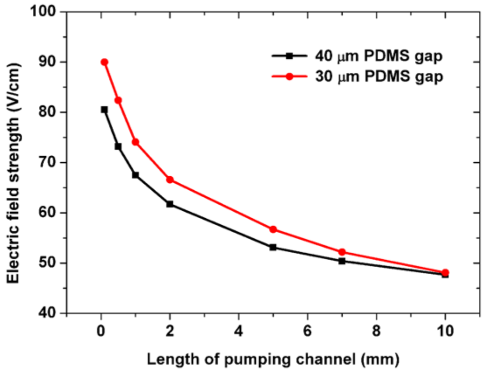

Fig. 10 (ESI) Electric field strength along pumping channel wall as a function of pumping channel length

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Electronic Supplementary Information 2 (ESI 2)

Movie ESI: A test movie for 7 s describing fluorescent particle movements in the electroosmotic flow in the pumping channel, as shown in Fig. 5. Applied voltage: 50 V. Scale bar: 40 μm.