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A novel diaphragm micropump actuated by conjugated polymer petals: Fabrication, modeling, and experimental results

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ABSTRACT

Micropumps have promising applications in biomedical devices and micro total analysis systems. Conjugated polymer actuators provide an important potential mechanism for realizing micropumps because of their amenability to miniaturization and low actuation voltages. In this paper we present a novel, conjugated polymer petal-actuated diaphragm micropump, which is in contrast to the typical diaphragm design of using a single piece of soft actuation material clamped at all edges. We show through analysis and experiments that the new design, by alleviating the edge constrains, can provide significantly larger diaphragm deformation and consequently higher flow rate. A physics-based, control-oriented model is developed to predict the diaphragm deformation and the flow rate given the actuation voltage input. Experiments conducted on a polypyrrole (PPy)-actuated micropump, fabricated through PDMS-based MEMS processes, have validated the dynamic model. A maximum flow rate of 1260 μL/min is achieved for the petal-actuated diaphragm pump under an actuation voltage of 4 V, while in comparison, the pump with traditional diaphragm design generates no observable flow under the same voltage.

1. Introduction

With the advances in microfabrication technologies, micropumps have received extensive attention over the past three decades because of their potential applications in drug delivery, biological and chemical analysis, microelectronics cooling, and space exploration [1]. The actuation mechanisms, fabrication methods, and applications for micropumps have been surveyed in several recent review articles [1–4]. Micropumps can be classified into *displacement pumps*, where the pressure forces are exerted through some moving boundaries, or *dynamic pumps*, where energy is imparted into the working fluid in other means [1]. A related classification is *mechanical pumps* versus *non-mechanical pumps*, depending on whether the pumping mechanism requires moving parts [4].

A predominant class of micropumps operates through periodic displacement of a flexible diaphragm, which changes the volume and thus the pressure of the pumping chamber. Diaphragm movement has been realized through a number of actuation methods, such as electrostatic [5,6], piezoelectric [7–9], thermopneumatic [10–12], shape memory alloy [13,14], electromagnetic [15], liquid–vapor phase change [16], and P(VDF-TrFE)-based electroactive polymer actuation [17]. Pumping can also be achieved by dragging ions in the fluid with electromagnetic fields, examples of which are electrohydrodynamic [18], magnetohydrodynamic [19], and electroosmotic [20] micropumps. Additional reported mechanisms for micropumps include electrowetting [21], bubble expansion and collapse [22], ultrasonic flexural plate waves [23], and evaporation [24]. More information about various micropumps can be found in [1–4] and the references therein.

Ionic electroactive polymers (EAPs), such as conjugated polymers [25–28] and ionic polymer–metal composites (IPMCs) [29–33], have emerged as promising, soft sensing and actuation materials for MEMS devices, robots, and biomedical systems. These materials can produce large deformation under low actuation voltages (several volts), which makes them an attractive actuation choice for diaphragm micropumps. IPMC-actuated micropumps have been studied in simulation [34] and in experiments [35,36] by a few research groups, and a conjugated polymer-actuated diaphragm pump has also been reported [37]. EAP-based micropumps have typically adopted a whole diaphragm design, where a single piece of EAP clamped at all edges acts as the pumping diaphragm [17,35–37]. These edge constraints, however, severely limit the displacement of the diaphragm and thus the pumping performance. Nguyen et al. proposed a flexible support structure for an IPMC diaphragm, which reduced the edge constraints and resulted in higher flow rates [36].

In this paper, we present a novel, conjugated polymer petal-actuated diaphragm micropump, which is in contrast to the typical whole diaphragm design [17,35–37]. We show through modeling analysis that the new design, by alleviating the edge constraints, can provide significantly larger diaphragm deformation

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and consequently the higher flow rate. In particular, an analytical model is developed to capture the relationship between the flow rate and the actuation voltage, which includes three parts: an admittance module, an electromechanical coupling module, and a mechanical module. The mechanical module for the cases of both a petal-shape diaphragm and a whole diaphragm is developed using the energy method [38], which incorporates the elastic energy stored in the diaphragm and the work done on the fluid by the diaphragm. The final model for the petal-shape diaphragm pump, after model reduction, is represented as a finite-dimensional transfer function that captures the fundamental physics of conjugated polymer actuators and their interactions with flexible diaphragm and fluid. It will be instrumental in the control design for the pump.

The rest of the pump is fabricated through PDMS-based MEMS processes. Experiments are conducted to evaluate the pump performance and the effectiveness of the model. Both a whole polypyrrole (PPy) diaphragm and a PPy petal-actuated diaphragm are used to test the flow rate in the same pump. While the single PPy diaphragm cannot generate an observable flow, the petal-actuated diaphragm can generate a maximum flow rate of 1260 μL/min and a maximum backpressure of 1.3 kPa under an actuation voltage of 4 V. Furthermore, the measured admittance, deformation curvature, and flow rate are found to match the models well. The complete model predicts that there is an optimal operating frequency for generating the largest flow rate, which is also verified in experiments. The power efficiency of the presented micropump, in terms of power consumed per flow rate, is about four times of that for the PPy-actuated whole diaphragm pump reported in [37].

The remainder of the paper is organized as follows. The design and fabrication of the micropump are described in Section 2. Model development is carried out in Section 3. Experimental results on pump performance and model validation are presented in Section 4. Finally, future work and concluding remarks are provided in Section 5.

2. Design and fabrication of micropump

2.1. Diaphragm designs

In a typical design of EAP-based pumping diaphragm, one uses a single EAP plate as the diaphragm to seal the pump chamber directly. The edge of the plate is mechanically fixed with electrodes on both sides. However, the strain of the middle-plane will be nonzero due to the restriction at the edge, which implies that a significant portion of energy will be required to stretch the middle-plane. The latter constrains the displacement of the diaphragm in the vertical direction. Detailed analysis will be shown in Section 3.

A new design is thus proposed here for the generation of large out-of-plane deformation, as illustrated in Fig. 1. A passive membrane with low stiffness is used to seal the chamber. Then a conjugated polymer plate is cut into the shape of petals and bonded to this passive layer. When the voltage is applied, the conjugated polymer petals will bend together to move the elastic diaphragm

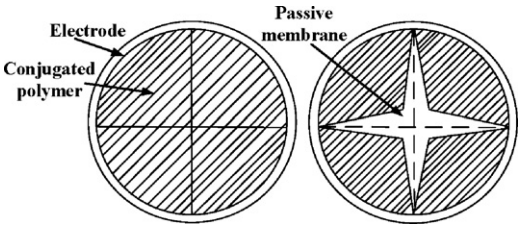

Fig. 1. Schematic representation of a petal-shape pumping diaphragm (top view). Left: before actuation; right: upon actuation.

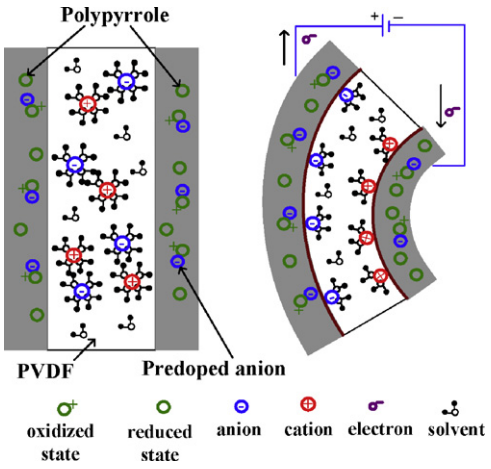

Fig. 2. Illustration of the actuation mechanism of a trilayer polypyrrole actuator. Left: the sectional view of the trilayer structure; right: bending upon application of a voltage.

and generate pressure changes inside the chamber. Therefore, it is the passive layer instead of the conjugated polymer that is being stretched, and one can choose a passive layer material with low Young's modulus to significantly reduce the energy required to stretch the middle-plane.

2.2. Fabrication and assembly of micropump

2.2.1. Fabrication of PPy actuator

In this paper we use a trilayer-structured PPy actuator as the pumping mechanism. The trilayer PPy actuator is illustrated in Fig. 2. On both sides of the actuator are the PPy layers (30 μm each) doped with anions $TFSi^-$, which were electrochemically deposited on the polyvinylidene fluoride (PVDF) layer (110 μm thick). The PVDF layer is amorphous and porous, which serves both as a substrate and a storage tank for the electrolyte. The electrolyte used in this paper is 0.1 M lithium triflouromethanesulfonimide (Li^+TFSI^-) in the solvent propylene carbonate (PC).

When a voltage is applied across the actuator, the PPy layer on the anode side is oxidized while that on the cathode side is reduced. The reduction–oxidation (redox) process can be described as

$$\begin{aligned} &\text{Oxidation}: \quad PPy + TFSI^- \rightarrow PPy^+TFSI^- + e^- \\ &\text{Reduction}: \quad PPy^+TFSI^- + e^- \rightarrow PPy + TFSI^-, \end{aligned}$$

where PPy represents the neutral state of polypyrrole, PPy^+ denotes the oxidized state, PPy^+TFSI^- indicates that $TFSI^-$ is incorporated into the polymer, and e^- denotes an electron. The different volume changes in the two PPy layers lead to bending of the actuator, as shown in Fig. 2(right).

Fabrication of trilayer conjugated polymer actuators is achieved by electrochemically oxidizing pyrrole monomer from a solution to grow PPy layers on either side of a gold-coated porous PVDF film, which acts as the working electrode. The porous PVDF films, obtained from Sigma–Aldrich, has a thickness of 110 μm with pore size of 0.45 μm. It is coated with a thin layer of gold (approximately 100 nm) via sputtering. This ensures a good conductivity therefore good electrochemical growth of PPy. The electrolyte is a solution of 0.1 M pyrrole, 0.1 M Li^+TFSI^- in propylene carbonate (PC) with 0.5 w/w% water. Note that the solution with Li^+TFSI^- will dope the PPy with $TFSI^-$. This fabrication approach follows that in [39,40]. The dopant can be changed to other ions, such as PF_6^-, by changing Li^+TFSI^- to the salts containing those ions.

A potentiostat (Omni 101B, ESA Biosciences Inc.) is used in the electrochemical deposition, which keeps the potential of the