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Soft dielectric elastomer actuator micropump

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ABSTRACT

This paper presents a miniaturized soft dielectric elastomer actuator (DEA) micropump which was demonstrated in microfluidic application. A strain-induced pre-stretched DEA undergoes expansion when subjected to high voltage, providing a two-way actuation in the presence of a pull-up spring. The DEA has been integrated with a microfluidic device with a diffuser element that enables it to pump the liquid in a controlled manner. At 4.2 kV applied voltage, a maximum deflection of 0.42 mm has been recorded, whereby a higher voltage causes the DEA layer to show severe wrinkle formation before it ruptures and fails. The dynamic response deflection of each repetitive actuation cycle has achieved high reliability at the low operating frequencies of 0.1 Hz and 0.25 Hz respectively, with standard deviations of 1.4% and 1.25%. The performance of the device has been determined by measuring the effective deflection at each frequency cycle. The experimental characterization of the fabricated micropump has shown a maximum flow rate of 42 μL/s at an optimum operating frequency of 3 Hz.

1. Introduction

Micro electromechanical systems (MEMS) technology has undergone various evolutions in the context of microfluidic device fabrication and actuator integration for micropump production. The associated applications have been expanded by utilizing flexible structures, such as in sensors and actuators. The technology has improved the practicalities of miniature and high performance device manufacturing, which includes innovation of integrated actuators and micropumps. Micropumps have been demonstrated in many applications and have been shown to be promising in microfluidic applications that requires high precision liquid dispensing [1,2]. Various actuation mechanisms such as piezoelectric, electromagnetic, electrostatic and shape-memory-alloy (SMA) actuators have been utilized for micropump development [3]. These actuators possess distinct properties and advantages that are utilizable in various applications according to respective requirements.

SMA actuators are incorporate several positive characteristics: large actuation force, high work density and mechanical robustness [4]. However, researchers have identified some drawbacks due to various constraints, which include fabrication complexity, heat requirement, poor response and low efficiency. In contrast, electrostatic actuation generally provides fast responses, has low power consumption, high reliability in avoiding contractions, and is considerably compatible with the microfabrication process [5]. Regardless, some functionality and technology limitations still exist for this method despite the warranted benefits, specifically its limited force and displacement [3]. Piezoelectric and electromagnetic actuators share a common attribute of large actuation forces and fast responses. However, they both also display distinct weaknesses; piezoelectric actuator has limited range of displacement, and has complex fabrication, whereas electromagnetic actuators consume high power, generates heat, and has poor controllability [3]. Nevertheless, various studies have been undertaken to show micropumps driven by electromagnetic actuators. For example, Getpreecharsawas et al. has reported on the fabrication of an electromagnetically actuated micropump with an integrated surface and bulk micromachining to evaluate the degree of robustness and study the specified volumetric changes [6]. Moreover, Yamaha et al. has described an electromagnetically actuated polymethylmethacrylate (PMMA) valveless micropump. The device has been equipped with a diffuser element that provides considerable deflection amplitude and reasonable flow rates, for water and air both [7]. It can be concluded that most of these existing actuation methods have practicality issues in regards to their bulky external support units and limited pumping performance. For ionic polymer metal composite (IPMC) actuators, their utilization of ionic particles movement under a specific voltage pose as a viable alternative. Their intrinsic properties include the ability to occupy small masses,

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remain flexible and compliant, alongside lower power consumption and high accuracy displacement [8]. However, these qualities also result in attributes that limit its reliability.

Dielectric elastomer actuator (DEA) is categorized as an electroactive polymer (EAP) that possesses large deformability and fast responses. Such features can be attributed to the very low power consumption, which simultaneously addresses any issues associated with other actuation methods [9]. Pelrine et al. has designed a technique that can investigate many smart materials and electromagnetics in the context of energy density [10]. It has been found that electroactive polymers like DEA possess an ideal energy density: it is similar to human muscles and is 8 times better than electromagnetic actuation. Therefore, these ideal features are the highlight of dielectric elastomer's potential as an alternative in actuator innovation [11]. Furthermore, DEA actuation has also been closely associated with an impressive force-to-weight ratio and high strain potential [9,12,13]. Other methods have also proposed that DEAs can theoretically achieve 80% overall efficiency under the constant charge operating mode [10]. Such characteristics have widened the range of its applications, especially as a replacement for the conventional electromagnetic motors. Its potential has rendered it a reliable candidate so as to resolve the practical issues faced by other actuation methods [14]. DEA is described as a flexible capacitor, which is composed of a pair of compliant electrodes applied on each side of a dielectric polymer [15]. Applying a high voltage between the two electrodes generates a compressive electrostatic stress, creating strain throughout the elastomeric dielectric. The thickness is subsequently reduced, and in cases of free-boundary conditions, surface expansion is seen [14]. DEA is a topic often reported on in literature, like Rosset et al. displaying large-stroke elastomer actuator using polydimethylsiloxane (PDMS)-based diaphragm suspended-membrane [14]. Furthermore, Bigue et al. has also explored the energy conversion efficiency of DEA based actuators [15]. Nevertheless, any useful applications pertaining to DEA has yet to be demonstrated.

In this paper,[1] the integrated approach of DEA actuation and micropump has been demonstrated. The characteristic of the DEA has been acquired by varying the thickness and diameter of the DEA membrane, followed by analyzing the respective performances based on the strain achieved. Multiple experiments have been conducted for the purpose of studying DEA characterization. The strain exhibited by the membrane has been recorded upon high voltage exerted on it. Furthermore, this paper also reveals the primary features offered by the DEA that are potential solutions for the practicality issues seen in other actuators. The out-of-plane structure exhibited on the DEA upon integration with a pull-up spring allows its implementation in micropumps as a driving force, whereas its simplified design can eliminate complex assembly methods. Moreover, the developed prototype has also experimented and analyzed the temporal flow control at different actuation frequencies.

2. Design and working principle

The actuation principles for the DEA and working principles of the micropump are different according to its structural configuration. Essentially, a DEA consists of a membrane sandwiched between two flexibly compliant electrodes (Fig. 1a). When a high voltage is applied, a potential difference is created and subsequently generates a compressive electrostatic force that causes its horizontal expansion. The electrostatic force present on the flexible membrane can be correlated with the driving voltage, V, the distance between the compliance electrodes, d, and the surface area between the electrodes, A [17]. The electrostatic force of the flexible membrane, F_e, is expressed in the following equation:

$$\boldsymbol{F_e} = \frac{1}{2}\boldsymbol{\varepsilon}_0\left(\frac{\boldsymbol{V}}{\boldsymbol{d}}\right)^2\boldsymbol{A} = \frac{1}{2}\boldsymbol{\varepsilon}\boldsymbol{V}^2\left(\frac{1}{\boldsymbol{D}_0-\boldsymbol{w}}\right)^2\boldsymbol{A} \quad (1)$$

where ε is the dielectric constant of the DEA, D_0 is the initial distance between the electrodes and w is the displacement in the transverse z-direction. This actuation principle is known as two-axis planar actuation as the structure is expandable in both x and y axes due to the strain induced by the high voltage (Fig. 1a).

As per Bigue et al., the DEA possesses a consistent membrane thickness and area, known as u and A respectively [15]. The film has a fixed volume, ψ, given by the equation;

$$\boldsymbol{\psi} = \boldsymbol{Ad} \quad (2)$$

The structural deformation occurs due to Maxwell stresses, which has been generated by electric charges located on the electrodes [15]. The total electrical charge, Q, is located on the film's electrodes under voltage, V, as given by;

$$\boldsymbol{Q} = \boldsymbol{CV} \quad (3)$$

where the actuator capacitance, C, can be calculated by the flat plate capacitor equation below;

$$\boldsymbol{C} = \boldsymbol{\varepsilon_d}\boldsymbol{\varepsilon}_0\frac{\boldsymbol{A}}{\boldsymbol{d}} \quad (4)$$

where ε_o is the permittivity of free space and ε_d is the relative dielectric constant of the DEA. The Maxwell pressure, P, due to the electrostatic attraction is given by [18];

$$\boldsymbol{P} = \boldsymbol{\varepsilon_d}\boldsymbol{\varepsilon}_0\left(\frac{\boldsymbol{V}}{\boldsymbol{d}}\right)^2 \quad (5)$$

For a one-axis planar actuation or a configuration with one fixed end, expansion and elongation can be seen in one direction only along the x- or y-axis (Fig. 1b). The bend type actuation has been described as one of its surface layer being restricted from moving, causing the structure to warp in the direction of the restricted surface (Fig. 1c). With minor changes, it is possible to configure different types of motion.

In this work, the DEA has been designed to form a diffuser micropump. Fig. 2a has illustrated the micropump design, which measures 30 mm in width, 40 mm in length and 7 mm in thickness. A laser cut method has been utilized to engrave the details on the membrane frame, whereas the diffuser valve has been carved on the base frame using a CNC machine. The micropump has been assembled using acrylic frames and the materials used for fabrication are VHB film (3 M, Minnesota, US), PDMS and carbon black powder (Graphene SuperMarket, Graphene Laboratories Inc., New York). Furthermore, the manufacturing of this micropump has employed polymer-based materials, in contrast of the conventional fabrication of mechanical micropumps using glass, silicon or plastic. Such move has been taken as polymer-based materials (i.e. PDMS and PMMA) are proven to show good biocompatibility, excellent physical and mechanical properties and are inexpensive. Moreover, VHB film has been used as the DEA due to its high strain properties and good performance in high actuation stress. PDMS is used as the insulation layer for suspended flexible membrane. With Young's modulus of 750 kPa and Poisson's ratio of 0.5, PDMS would serve as a good candidate to be used along with VHB film as flexible membrane. Additionally, Carbon Black Powder has been chosen as the conducting element due to its capability to deform alongside the flexible membrane.

[1] A portion of this manuscript has appeared as a conference abstract in [16] P. S. Chee, C. K. Mah, and M. S. M. Ali, Šoft dielectric elastomer actuator for micropump application,ïn *2016 IEEE 29th International Conference on Micro Electro Mechanical Systems (MEMS)*, 2016, pp. 561–564.