Effects of Fiber Stiffening to a Soft Actuator with PEDOT/PSS Electrode Films on Actuation Cycling Stability

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Abstract: In this work, we fabricated a fiber-stiffened soft actuator with PEDOT/PSS films as electrode. Embedding nylon fibers in the soft actuator successfully suppressed twisting deformations, resulting in a large and persistent actuation displacement. We evaluated the effects of the fiber spacing (1, 2, 3 and 4 mm) on the displacement and assessed the actuation displacement as a function of applied voltage (0.5, 1.0 and 1.5 V) and frequency (0.2 and 1 Hz) with an actuation time of 500 s. We demonstrated that the fiber-stiffened actuator with 2 mm fiber spacing exhibited steady actuation cycles (4.2 mm average displacement) in comparison with those with different spacings (1, 3, and 4 mm) and that without the fiber.

Key words: PEDOT/PSS, fiber-stiffened actuator, actuation behavior, stable deformation

1 Introduction

Microfluidic technology has attracted significant attention owing to the continual development of microelectromechanical systems (MEMS) and micro total analysis systems (μTAS) for biological analysis, chemical reactions, medical testing and diagnosis of diseases¹–⁷. Microfluidic devices are especially useful and effective tools to produce monodisperse emulsions for the formulation of food, cosmetics, and pharmaceuticals⁸–¹¹. They are also employed for the high precision and high-resolution separation/detection of microparticles/particle classification¹²,¹³. Advanced microfluidic devices require highly efficient active components/power sources (actuators) for pumping, valve control, and mixing to achieve precise control and on-demand release of fluids automatically¹⁴–¹⁶. In particular, the ionic electroactive polymer (i-EAP) actuator has been employed for developing micropumps, valves, and mixers in microfluidic devices¹⁷–¹⁹, owing to its unique advantages of low weight, easy miniaturization, and rapid conversion of electrical to mechanical energy with a low driving voltage²⁰–²².

For applications such as high-throughput separation and on-demand manipulation of fluids in microfluidic systems, stable actuation deformations of the micropumps and microvalves are essential. Although i-EAP soft actuators have outstanding advantages as power sources, there remains a demanding inherent obstacle. Undesirable deformations arise under applied voltage because the polymer-based actuator film is soft and flexible. For i-EAP actuators, it is often difficult to maintain stable and unidirectional deformations by restraining twisting/torsion, owing to their inherent characteristics of softness. As a typical i-EAP device, ionic polymer-metal composite (IPMC) actuators are candidates for microfluidic devices. However, numerous studies²¹–²³ found that the actuators exhibited twisting, rolling, whirling and non-symmetric bending deformations, resulting from irregular cracks and wrinkles on metal (Pt/Ag) electrodes and uneven distribution of the electric field. In our previous work²⁴,²⁵, we developed a paper polymer actuator using poly(3,4-ethylenedioxythiophene) doped with poly(4-styrenesulfonate) (PEDOT/PSS) as electrode films. Although the soft actuator exhibited displacement of 5.8 mm at low voltages (1.5 V)²⁶, it exhibited twisting deformation as the cycles increased and then its effective displacement gradually decreased in a minute. For the application of the polymer-based actuators as power sources in

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microfluidic systems, it is essential to control the actuation
deformation using a new approach.

To constrain the deformation direction of dielectric elastomer actuators, Suo and coworkers\textsuperscript{26, 27} introduced stiff fibers to the elastomer sheet. Unidirectional actuation was achieved by restraining the deformation in parallel to stiff fibers. Although the dielectric elastomer actuators operate under significantly higher voltages (~kV) with different working mechanisms, we considered this approach essentially applicable to paper actuators that drive at low voltage.

In this work, we fabricated fiber-stiffened PEDOT/PSS actuators to improve their actuation cycle stability. We evaluated the effects of fiber spacing (1, 2, 3 and 4 mm) on the suppression of twisting deformations. Moreover, we assessed the actuation displacement of the fiber-stiffened actuator with 2 mm fiber spacing as a function of frequency (0.2 and 1 Hz) and applied voltage (0.5, 1.0 and 1.5 V).

2 Experimental

2.1 Materials

The preparation of the PEDOT/PSS film used as the electrode material has been reported in a previous work\textsuperscript{25}. Aqueous PEDOT/PSS solution (3.3 wt%, 0.6 g, Sigma-Aldrich) with 1 wt% polyethylene glycol monooleyl ether (Tokyo Chemical Industry, Japan) was stirred at 200 rpm for 2 h with degassing. For degassing the solution, the at-
mosphere was suctioned down to about 30 kPa with a diaphragm aspirator. The vacuum was kept overnight. The polymer solution was poured in a PTFE petri dish with 30 mm inner diameter and dried at 60°C for 12 h and subsequently at 120°C for 3 h. Finally, the prepared PEDOT/PSS film was peeled off from the dish. Poly(diallyldimethylammonium chloride) solution (average MW = 4–5 x 10^5, 20 wt% in H_2O) was purchased from Sigma-Aldrich for use as polyelectrolyte layer. Nylon fibers with a diameter of 0.104 mm (VALCAN EXTRA H-10, Sanyo Nylon Co. Ltd., Japan)

Fig. 3 Deformations of (a) the actuator without fiber and the fiber-stiffened actuators with (b) 4 mm fiber spacing, (c) 3 mm fiber spacing, (d) 2 mm fiber spacing and (e) 1 mm fiber spacing at 1.5 V and 0.2 Hz during 100 cycles. The red arrows in the photos indicate the tip ends of the actuators.
were used for reinforcement. Figures 1(a) and (b) show the chemical structures of PEDOT/PSS and poly(diallyldimethylammonium chloride).

2.2 Fabrication of a fiber-stiffened PEDOT/PSS actuator

The fabrication process of a fiber-stiffened PEDOT/PSS actuator is shown in Fig. 1(e). Firstly, a 20 μm-thick PEDOT/PSS film (5) was used as a matrix electrode film. The detailed procedure of the PEDOT/PSS film preparation was described in the previous paper25. For the polyelectrolyte layer (4), the poly(diallyldimethylammonium chloride) solution was cast onto the prepared PEDOT/PSS film using a spin coater (type 1H-D7, Mikasa Co. Ltd., Tokyo, Japan) at 3000 rpm in 10 s. Following this, nylon fibers (3) were placed by hand in parallel with different spacings of 1–4 mm and covered with another PEDOT/PSS films (2) to form a sandwich structure with the electrode films. The spacings described here were approximate values. The fabricated composite fiber-stiffened PEDOT/PSS actuator was trimmed in a rectangular shape with a length of 20 mm and a width of 3 mm. Last, two copper foils (1) and (6) used as the metal electrodes were placed on the upper surface edge (2.5 mm) of the composite actuator. The working length of the actuator was 17.5 mm. Figure 2 shows the photos of the overview and the microscopic cross view of a fiber-stiffened actuator with 2 mm fiber spacing.

2.3 Electromechanical behavior tests (Measurements)

The upper end (2.5 mm) of the composite fiber-stiffened actuator was fixed to a beam. The copper electrodes were clipped with Kelvin clips that connected the device to the counter electrodes of a potentiostat (HAL-3001, Hokuto Denko Co. Ltd., Tokyo, Japan). A function generator (HB-305, Hokuto Denko Co. Ltd., Tokyo, Japan) was used to generate alternating square-wave voltages (±0.5, ±1, and ±1.5 V) and frequencies (0.2 and 1 Hz). Prior to each experimental run, the actuator was soaked in water, and the excess water was wiped away. The runs were recorded for 500 s by a digital video camera at 30 frames per second, and the video images were analyzed using ImageJ software. For untwisted actuation, the actuation displacement was evaluated horizontally from the resting position to the actuator tip, as shown in Fig. 1(d).

3 Results and Discussion

3.1 Effects of the fibers on actuation deformation

To investigate the effects of the fibers on actuation deformation, we prepared an actuator without fibers and the fiber-stiffened actuators with spacings of 1, 2, 3, and 4 mm. Figure 3 shows the deformations of the actuators at 1.5 V and 0.2 Hz during 100 cycles. As shown in Fig. 3(a), the actuator without fiber displayed evidently large twisting deformations during 20 to 100 cycles. The stripe-shaped actuator not only deflected from the fixed point, but also bent in the direction of the width (twisting). At the positions farther away from the fixed point, the actuator increasingly twisted during large cycle numbers.

Embedding fibers in the actuator suppressed the twisting deformation to various degrees depending on the fiber spacing. The actuator with 4 mm-spaced fibers (Fig. 3(b)) showed smaller twisting deformations than that without any fibers. However, it exhibited increased twisting (at the lower end) in the later cycles. For the fiber-stiffened 3 mm-spaced actuator (Fig. 3(c)), slight twisting deformation was still observed with a displacement decrease during 100 cycles. In contrast, the actuators with 2 mm and 1 mm fiber spacing (Figs. 3(d) and 3(e)) exhibited no distinct twisting for 100 cycles. These results demonstrate that the appropriate embedment of fibers in the actuators can effectively suppress twisting deformation and improve the actuation cycle stability.

In Fig. 4(a), the displacements are plotted as a function
Fiber-Stiffened PEDOT/PSS Actuators

J. Oleo Sci.

3.2 Effects of frequency and voltage on the actuation properties of the fiber-stiffened actuator

To evaluate the actuation displacement at different frequencies and voltages, the actuator with 2 mm fiber spacing was further examined.

Figure 5(a) shows the displacement of the 2 mm fiber-stiffened actuator as a function of working time at 0.2, and 1 Hz and a constant voltage of 1.5 V. In these frequency conditions, the actuator exhibited stable displacements for 500 s. As shown in Fig. 5(a), the average displacement was larger at 0.2 Hz (4.2 mm) than that at 1 Hz (1.4 mm). In the experimental condition of 1 Hz, the applied voltage was reversed before the actuator reached the maximum displacement. In the case of 0.2 Hz, the driving time (2.5 s) before the applied voltage was reversed was longer than that in 1 Hz (0.5 s). Therefore, the average displacement of the actuator in 0.2 Hz was larger than that in 1 Hz.

Figure 5(b) displays the effects of the applied voltage on the actuation at 1 Hz. The displacement became larger as the applied voltage increased from 0.5 to 1.5 V. When a higher voltage is applied to the capacitor-type actuator, the charge of the electrodes increases, and more chloride ions associated with water move toward the anode. The increased water content in the anode side results in increased swelling, which induces a larger displacement. At the applied voltages of 0.5, 1.0, and 1.5 V, the 2 mm fiber-stiffened actuator displayed a stable actuation displacement up to 500 s. At 0.5 and 1.0 V, stable average displacements of 0.3 and 0.9 mm were observed, respectively. At 1.5 V, the actuator showed a larger displacement (1.4 mm) as well.

4 Conclusions

In this study, we fabricated nylon-fiber-stiffened actuators with different fiber spacing (1, 2, 3, and 4 mm). In the case of the fiber-stiffed actuators with 1 and 2-mm fiber spacing, embedding the fibers in the actuators effectively suppressed twisting deformation, and stable displacements were confirmed for 500 s. Furthermore, we evaluated the effects of the frequency (0.2 and 1 Hz) and applied voltage (0.5, 1.0, and 1.5 V) on the displacement of the fiber-stiffened actuator with 2 mm fiber spacing. As a result, we demonstrated that the actuation displacement could be controlled by changing the frequency and applied voltage.

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