

Sensor Response of Polypyrrole Trilayer Benders as a Function of Geometry

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ABSTRACT

Trilayer polypyrrole benders are capable of generating voltages and currents when applied with an external force or displacement, demonstrating potential as mechanical sensors. Previous work has identified the effects of dopant and electrolyte on the sensor output, and a 'deformation induced ion flux' model was proposed. The current work aims to identify the change in sensor response with input amplitude and bender geometry as a function of frequency. The current and charge output from the trilayer benders were found to increase proportionally with input displacement and bender strain for multiple input frequencies, indicating linearity. Sensitivities of the current and charge output have also been calculated in response to strain, and are found to increase as the volume of the conducting polymer is increased. Some guidelines for sensor geometry are then suggested, using the identified sensitivities as a guide.

Keywords: Conducting polymer, bender, reverse actuation, sensor, characterization

1. INTRODUCTION

Conducting polymers have been shown to generate a voltage and current when applied with an external force or displacement, the reverse of the more widely studied actuation properties. This behavior has been identified for conducting polymer films [1, 2] and laminated structures [3, 4] and demonstrates the potential of conducting polymer devices as mechanical sensors. However, these sensors must be fully characterized before they can be used in practical applications.

Trilayer benders [5] are laminated conducting polymer devices, comprising of two polypyrrole (PPy) layers separated by an inert, porous substrate which doubles as self-contained electrolyte storage, allowing the device to operate in air. Previous studies into the sensor response of the trilayer benders have identified the effect of dopant and electrolyte on sensor output [4], and low frequency characterization has been performed [3] for three different length benders.

This paper continues previous work by identifying the current and charge output of the trilayer bender sensor as a function of frequency, geometry, input amplitude and strain for a single electrolyte concentration. Linearity has been confirmed for multiple input frequencies. The sensitivity of the current and charge response have been determined for multiple trilayer dimensions and are used to suggest design criteria for sensor geometry.

2. EXPERIMENTAL SETUP

2.1. Bender structure and synthesis

The trilayer bender is used primarily in this study, comprising of a porous poly(vinylidene fluoride) (PVDF) substrate separating two polypyrrole (PPy) layers, as shown in Fig. 1.

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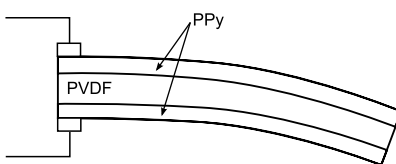


Fig. 1: Trilayer bender structure

The trilayer benders were manufactured using an electrochemical deposition process. The bare PVDF (Millipore Immobilon) was first sputter coated on both sides with gold, then fitted to a stretcher frame. A glass cell was filled with a polymerization solution of 0.1M pyrrole (Merck), 0.1M Lithium bis(trifluoromethanesulfonimide) (LiTFSI, 3M) and 1w/w% water in Propylene Carbonate (PC, Aldrich), that had been deoxygenated using N_2 for 20 minutes. The PVDF and stretcher were placed in the cell as the working electrode, with a stainless steel mesh as a counter electrode, and then cooled for 8 hours to -35°C . The conducting polymer was then deposited using a galvanostat (Princeton Applied Research, model 363) at a constant current density of $0.1\text{mA}/\text{cm}^2$ for 12 hours. Upon completion of the polymerization, the PPy coated PVDF was removed from the stretcher frame, washed with acetone and soaked in 0.1M LiTFSI in PC. Benders were cut from the bulk sheet as required.

2.2. Experimental setup

The sensor response of the bender was identified by applying a displacement input to the tip and measuring the current output (Fig. 2). A National Instruments data acquisition (DAQ) board (model NI6229) and custom LabView software were used to generate the reference displacement, used by the Dual-Mode Lever Arm system (Aurora Scientific, model 300C-LR) to control lever position. Platinum electrodes were used to clamp one end of the trilayer and provide electrical connections to the individual PPy layers, each connected to an eDAQ potentiostat (model EA161) operating in two-electrode Zero-Resistance Ammeter mode. An eDAQ datalogger (model ED821) was used to record the current signal. The displacement input signal for all tests was a variable frequency sine wave swept between 0Hz and 40Hz at a rate of 2Hz/s.

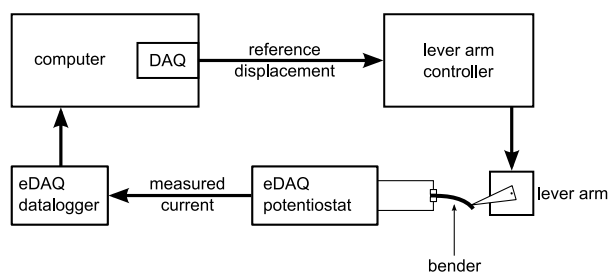


Fig. 2: Outline of experimental setup

Small magnets were used to fix the lever arm to the bender tip, as shown in Fig. 3, ensuring constant connection for the whole actuation cycle.

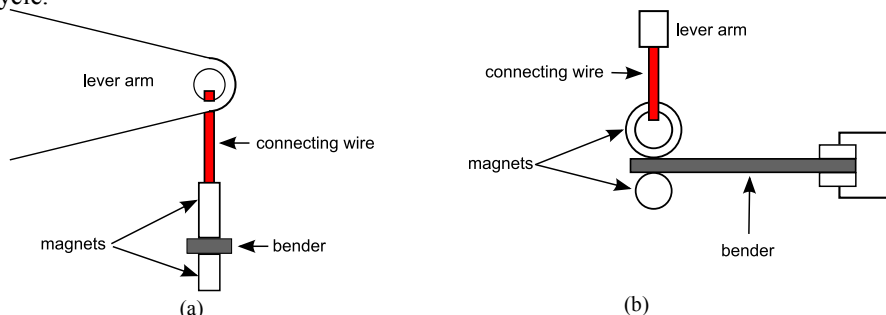


Fig. 3: Schematic of the (a) front and (b) side view of the lever arm setup

The eDAQ Chart software package was used to interface with the eDAQ datalogger and export the measured current signal for further processing. MATLAB was used to numerically integrate the current to obtain the charge response, and the frequency response of both signals was calculated using the Signal Processing toolbox.

3. EXPERIMENTAL RESULTS

3.1. Polypyrrole thickness

The PPy thickness was identified using a calibrated microscope and an example micrograph is shown in Fig. 4. The average PPy thickness was 20 μ m on each side and the PVDF thickness approximately 100 μ m.

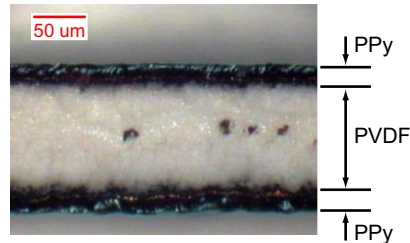


Fig. 4: Typical micrograph of PPy trilayer cross-section

3.2. Frequency response

The sensor response of the trilayer bender was identified as a function of input frequency, an example of which is shown in Fig. 5(a) for the current and Fig. 5(b) for the calculated charge generated by a 5mm long, 2mm wide bender. The peak current response occurs at approximately 2.5Hz.

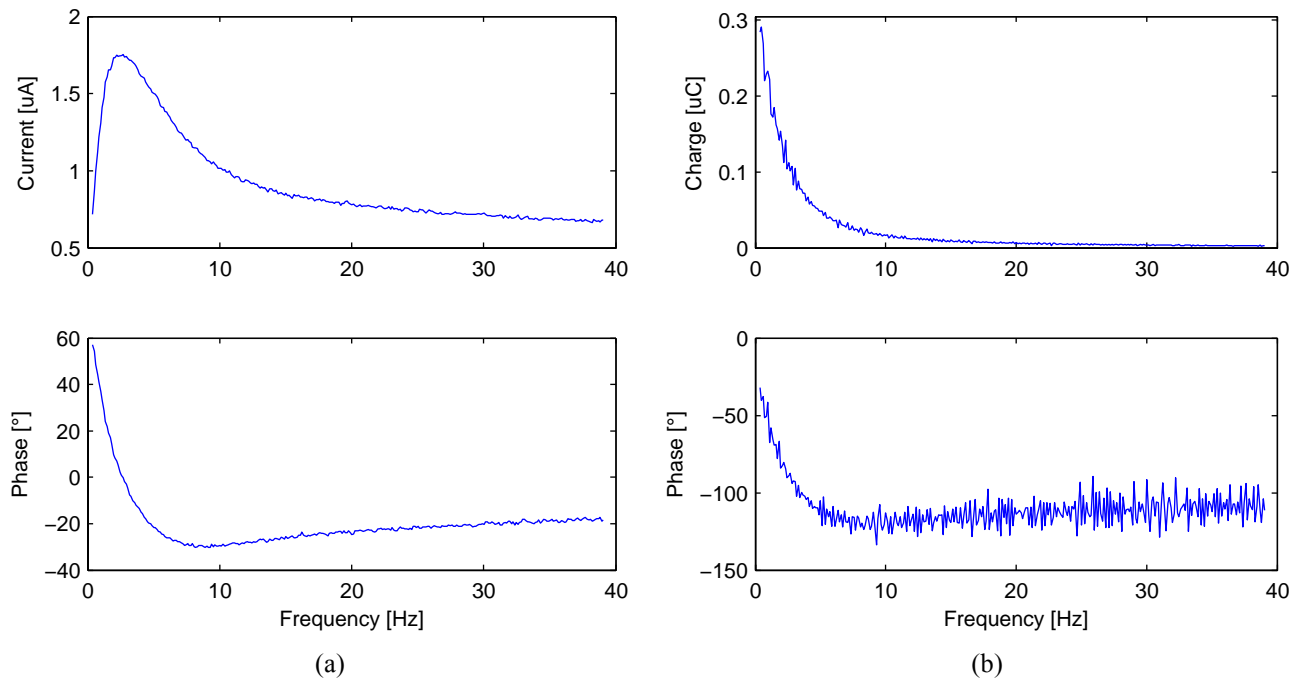


Fig. 5: Example of (a) identified current response and (b) calculated charge response as a function of frequency, for a 5mm long, 2mm wide bender with a ± 0.15 mm input.

3.3. Linearity

The frequency response of the trilayer bender was obtained for multiple input amplitudes to identify the linearity of the sensor. Sample responses are shown in Fig. 6(a) for current and Fig. 6(b) for charge.

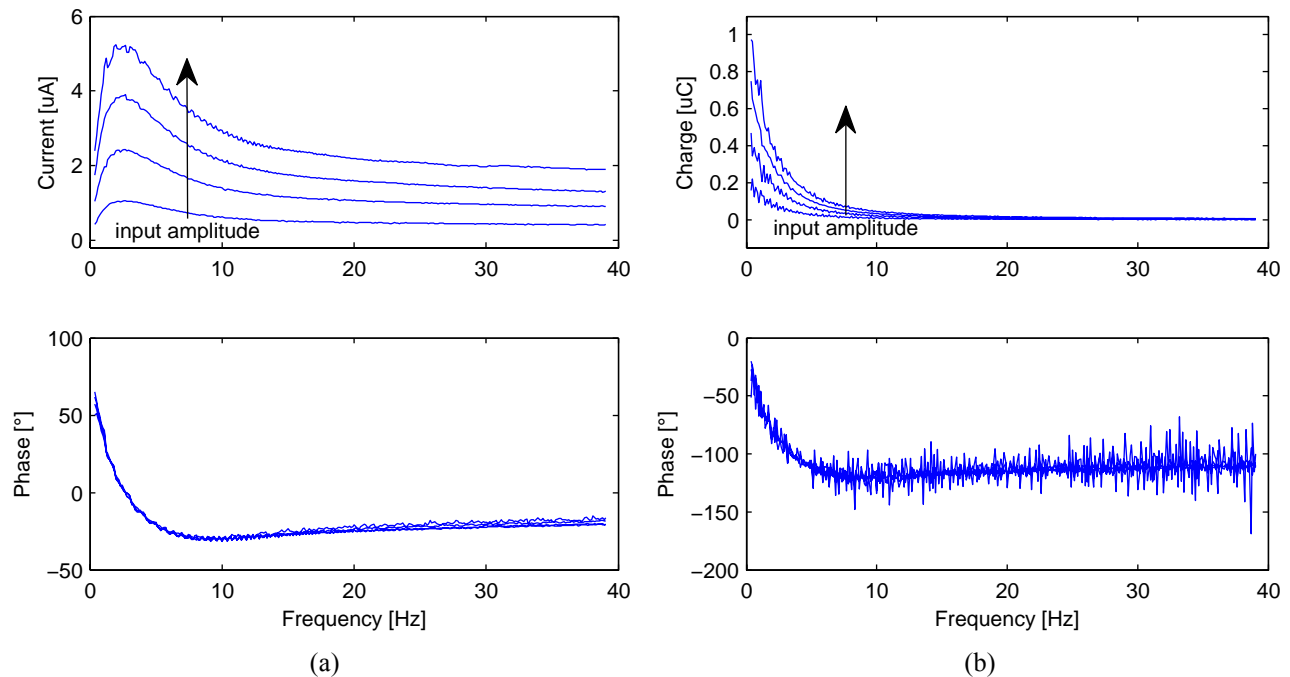


Fig. 6: (a) Current and (b) charge frequency response of a 5mm long, 2mm wide trilayer bender for input amplitudes of ± 0.1 mm, ± 0.2 mm, ± 0.3 mm and ± 0.4 mm.

The current and charge at four input frequencies have been identified as a function of input amplitude, as shown in Fig. 6. Trendlines have been fitted to the linear portion of the response, as shown by the solid lines, and the gradients are presented in Table 1.

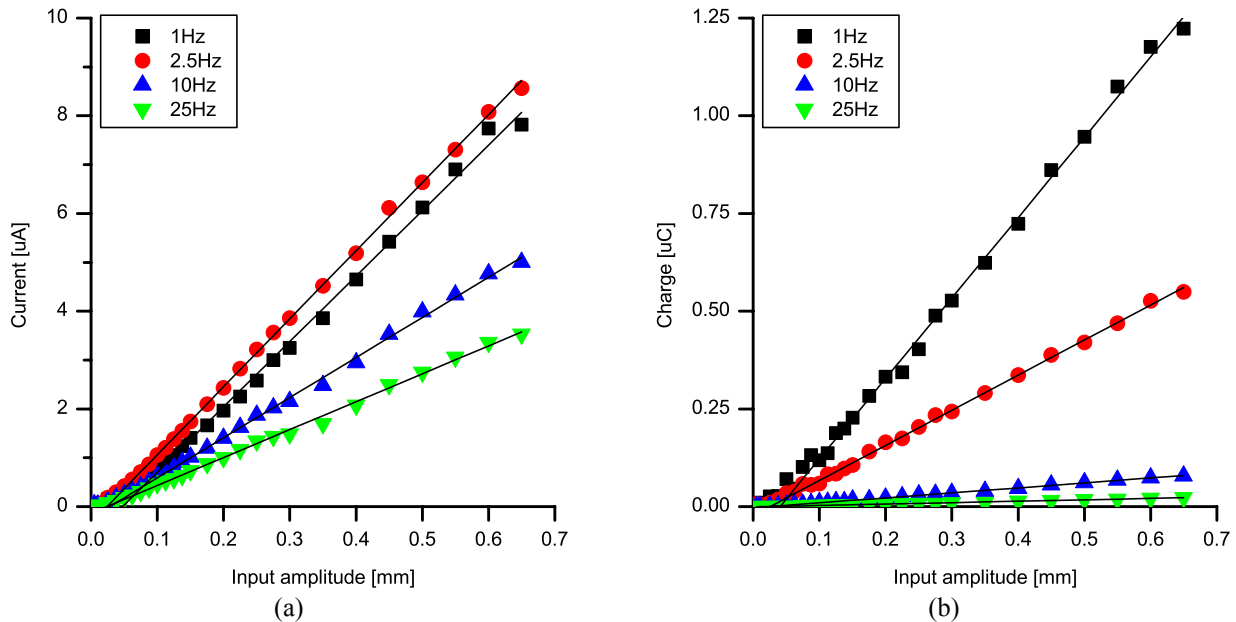


Fig. 7: The (a) current and (b) charge response at multiple frequencies for a 5mm long, 2mm wide trilayer bender as a function of input amplitude. Trendlines have been fitted to the linear component of each response.

Table 1: Gradients of charge and current output for multiple input frequencies

Frequency [Hz]	Current [uA/mm]	Charge [uC/mm]
1	13.39	2.06
2.5	13.93	0.90
10	8.21	0.13
25	5.71	0.04

The elongation of each PPy layer during bending is dependent on the length of the bender and the displacement of the free end. The strain profile of the trilayer bender is shown in Fig. 8, and the strain through the trilayer profile at the electrode clamp can be calculated using (1), where l is the bender length, x is the input displacement and y is the distance from the neutral axis. The strain at the PPy midpoint has been used in all cases for the purposes of comparison, corresponding to $y=60\mu\text{m}$ and represented as a percentage (2).

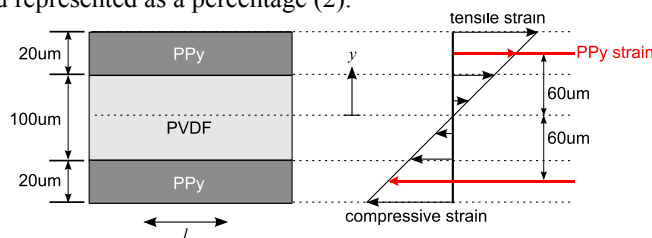


Fig. 8: Strain profile of a cross-sectional element of the trilayer bender

$$\varepsilon = \frac{3xy}{l^2} \quad (1)$$

$$\varepsilon_{\%} = \varepsilon \times 100 \quad (2)$$

The current output at 2.5Hz plotted against average PPy strain is shown in Fig. 9(a), with a fitted linear trendline. The corresponding charge at 2.5Hz is plotted in Fig. 9(b).

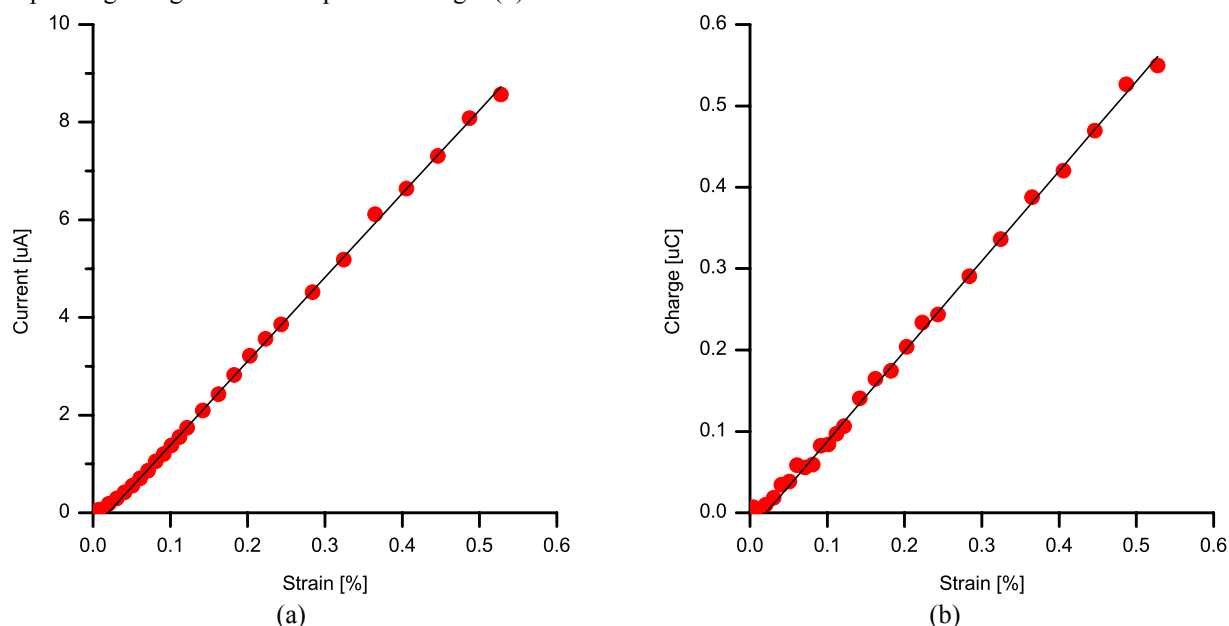


Fig. 9: (a) Current and (b) charge output at 2.5Hz as a function of strain for a 5mm long, 2mm wide trilayer bender. Trendlines have been fitted to the linear component of the response.

3.4. Effect of geometry

To identify the effect of geometry on sensor response, the current and charge output have been obtained as the dimensions of the trilayer were varied. The current generated at 2.5Hz is presented in Fig. 10(a) as a function of strain, and the current normalized against the volume of PPy (current density) at the same frequency is presented in Fig. 10(b).

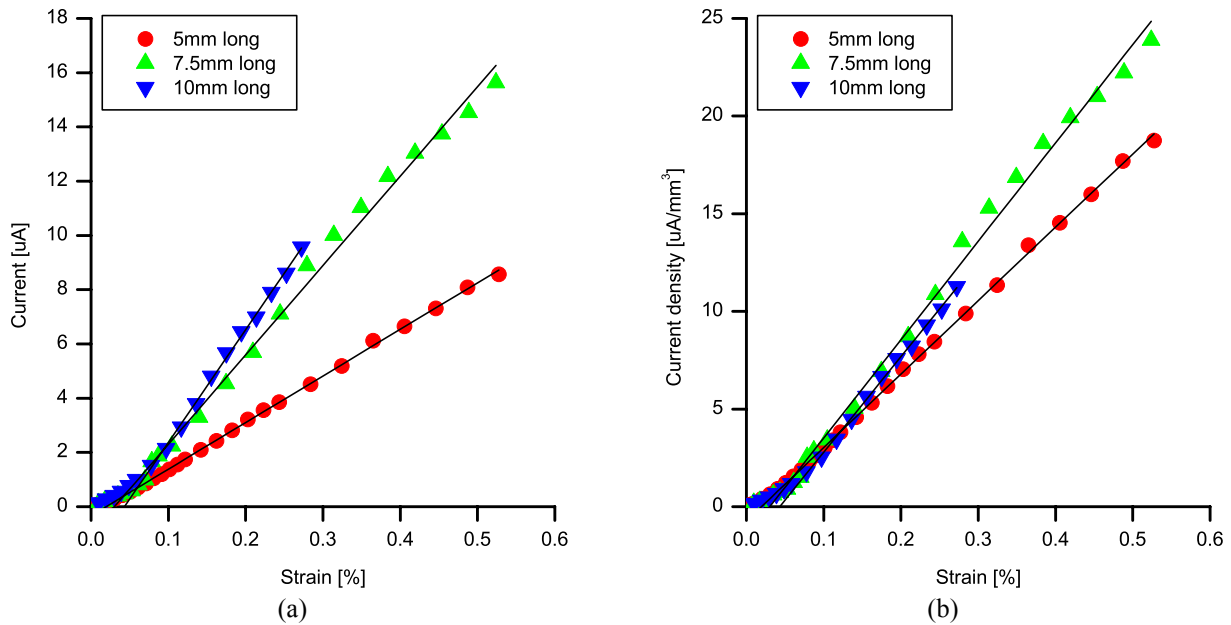


Fig. 10: (a) Current and (b) current density at 2.5Hz for various length trilayer benders, all 2mm wide. Trendlines have been fitted to the linear part of the response.

Current (Fig. 11(a)) and current density (Fig. 11(b)) at 2.5Hz have been identified for a 2mm and 4mm wide trilayer bender, both 5mm long. Linear trendlines have been fitted to both responses, with gradients shown in Table 2.

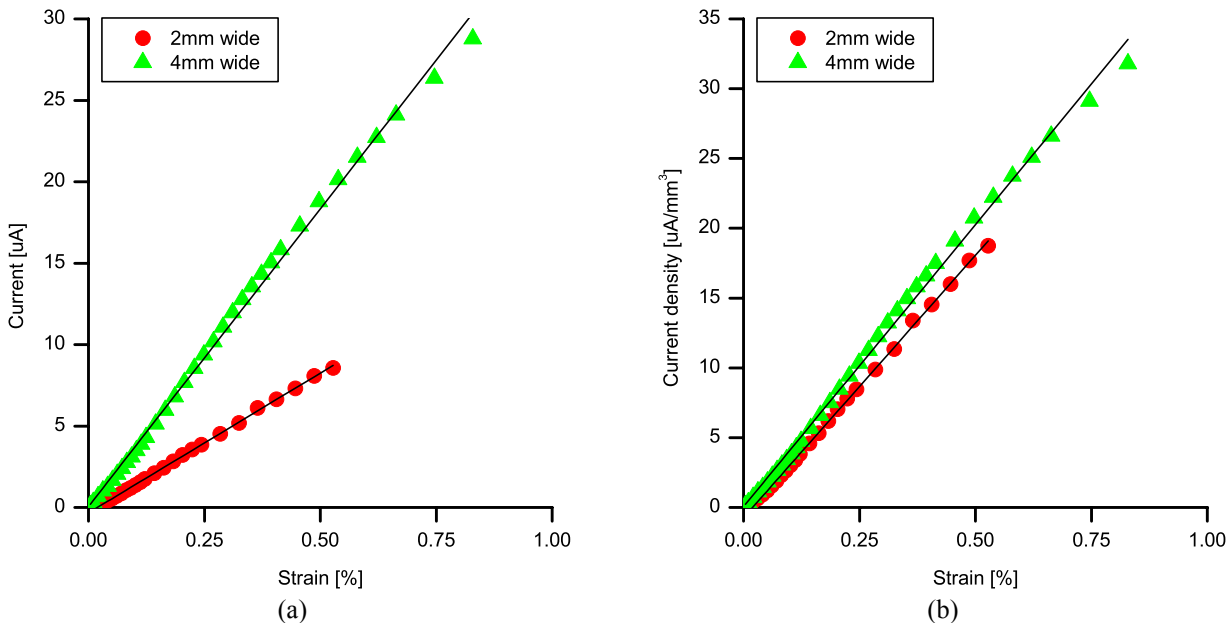


Fig. 11: (a) Current and (b) current density at 2.5Hz for a 2mm and 4mm wide bender, both 5mm long. Trendlines have been fitted to each response.

The charge generated per unit volume of PPy has been calculated at 2.5Hz for different bender geometries, presented in Fig. 12(a) for the variation in length, and Fig. 12(b) for the variation in width. Linear trendlines have been fitted in all instances, and the coefficients are shown in Table 2 (with additional gradients provided for the 4mm lengths).

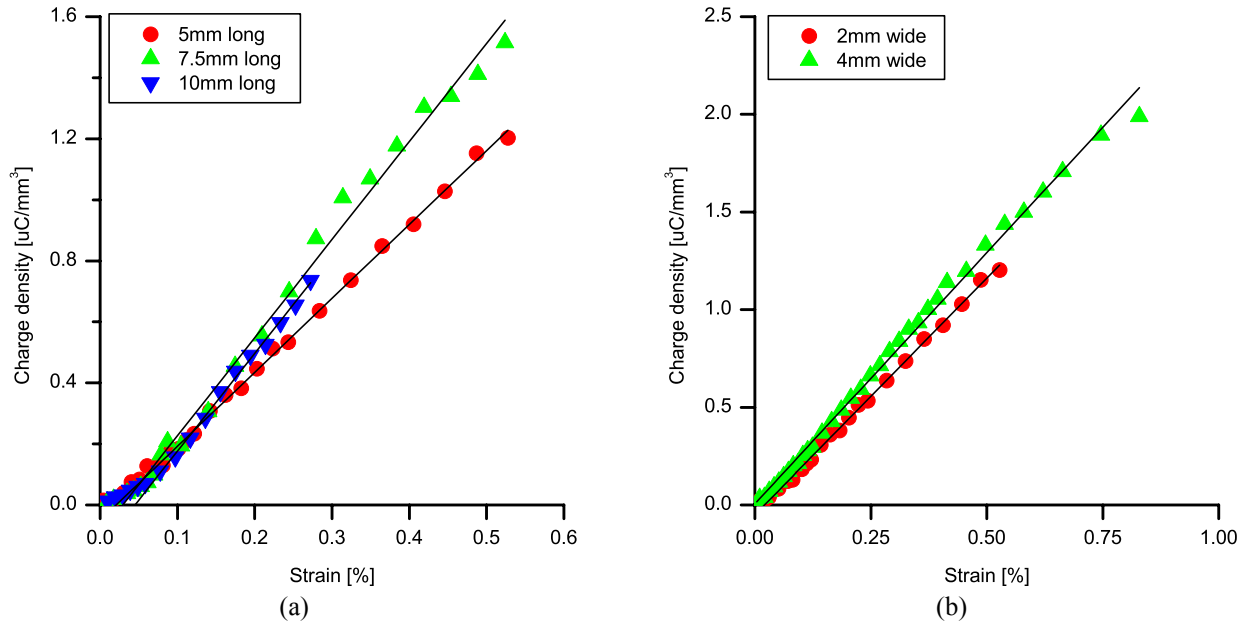


Fig. 12: The charge at 2.5Hz as a function of PPy elongation, for variations in (a) length of a 2mm wide bender and (b) width of a 5mm long bender. Linear trendlines have been identified for all responses.

Table 2: Gradients for the identified current and charge responses to PPy elongation

Length [mm]	2mm wide					4mm wide				
	uA/mm	uA/%	(uA/mm ³)/%	uC/%	(uC/mm ³)/%	uA/mm	uA/%	(uA/mm ³)/%	uC/%	(uC/mm ³)/%
5	13.93	17.17	37.58	1.11	2.42	30.31	36.57	40.38	2.33	2.57
7.5	11.51	32.96	50.36	2.10	3.21	15.20	43.16	33.10	2.75	2.11
10	8.09	41.59	48.96	2.72	3.20	12.79	66.42	38.90	4.26	2.50

The sensitivity of the trilayer bender can be defined as the proportional change in sensor output to a change in sensor input and corresponds to the gradients presented in Table 1 and Table 2.

4. DISCUSSION

4.1. Linearity

Sensor response has been identified as a function of input amplitude for multiple frequencies, as shown in Fig. 7, which indicate the current and charge output is linear. The identified linearity did not apply to the entire input amplitude range, with some deviation at low input amplitudes, as shown in Fig. 13. This occurs at strains below 0.075% for the 2mm wide trilayer and corresponds to charge densities below $0.5\mu\text{C}/\text{mm}^3$.

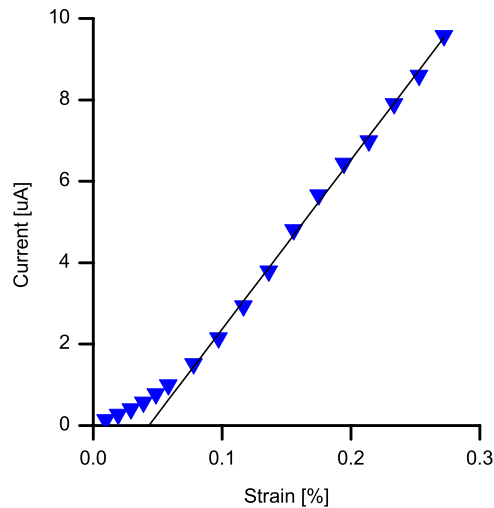


Fig. 13: Current output as a function of strain at 2.5Hz for a 10mm long, 5mm wide trilayer bender

While the linearity of the sensor response holds for multiple frequencies, the sensitivity is dependent on input frequency, as shown in Table 1. Prior knowledge of the frequency response will be required to identify the magnitude of displacement in any dynamic application.

4.2. Effect of geometry

The dependence on the sensor response on geometry has been identified by modifying the length and width of the trilayer bender and calculating the sensitivity of the output. Increasing the length of the trilayer bender was found to decrease the sensitivity of the current and charge output to input displacement, as the strain of the PPy layers decreases with length for a constant input displacement. When the trilayer benders are compared in terms of strain, the sensitivity of the output to PPy strain increases with length, as a greater volume of polymer is activated; normalizing the current and charge output to the volume of PPy produces similar ratios to strain for all lengths. This finding is similar to previous work on the actuation properties of conducting polymer films, where the strain generated was found to be proportional to the applied charge density [6].

Increasing the width of the trilayer bender also increases the sensitivity of the device, as the volume of PPy is also increased. The highest sensitivity trilayer tested for either charge or current output corresponds to a 10mm long, 4mm wide trilayer bender in response to PPy strain.

4.3. Geometry improvements

The highest sensitivities of the trilayer benders have been identified for current output as a function of strain. It is suggested that the length of the trilayer bender be selected to balance between the strain generated and volume of the polymer, as longer benders have a greater volume of polymer but require a greater input displacement to produce the same amount of strain.

The width of the sensor should be increased as far as practicable, as this will maximize the volume of polymer in the sensor and improve sensitivity. The width would not influence the level of strain generated in the PPy; however, excessively wide benders may experience twisting if the input force is not centered, producing torsional strains and modifying the sensor response.

5. CONCLUSIONS

The frequency response of the trilayer benders has been identified for both current and charge output, and linearity with input displacement and strain confirmed for multiple frequencies. It has also been identified that the sensitivity of the bender is dependent on the volume of conducting polymer. Based on these findings, some suggestions for selecting the geometry of the sensor have been suggested.

Future work will (i) further characterize the sensor response, considering the variation in sensor output with time, useful range of the sensor and the effects of electrolyte concentration on frequency response, (ii) establish mathematical models to incorporate fundamental mechanoelectrical and geometrical properties, and (iii) develop and test the efficacy of conducting polymer mechanical sensors in practical applications.

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