A wireless powered electroactive polymer using magnetic resonant coupling

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Abstract. This paper reports an ionic polymer-metal composite (IPMC) soft actuator that is controlled and powered in a wireless manner. IPMC is an ionic electroactive polymer (EAP) that can be actuated at a low voltage, fast response and miniaturized, therefore, attracts significant interest that have led to extensive investigations, especially for biomedical application. The device design utilizes magnetic resonant coupling as the wireless powering scheme. A planar based LC receiver circuit and DC rectifier circuit are fabricated using double sided and single sided copper-clad flexible polyimide sheets, respectively. The fabricated IPMC cantilever is bonded to the DC rectifier circuit and performs unimorph motion when the exposed magnetic field (generated by the transmitter circuit) matches the resonant frequency of the LC receiver circuit, ~25 MHz. Experiment wireless operation of the fabricated LC receiver circuit shows a maximum induced DC voltage of ~2.3 Vdc. The cantilever deflection is measured as 66 μm at ON-OFF activation cycle with 0.6 W RF output power.

1. Introduction
Electroactive polymers (EAPs) [1] based muscle-alike actuator offers a broad opportunity for flexible and more degree of freedom (DOF) in biomedical robotic design. Compared to other types of smart polymer actuators such as shape memory polymer, EAPs pose larger strain, faster speed and good efficiency. Ionic polymer metal composite is an EAP, consists of a thin ion exchange polymer membrane sandwiched between two metal electrodes. IPMC can be actuated at very low voltage, fast response and ease of miniaturization [2]. Moreover, the biocompatible and soft muscle-alike actuation properties allow it to be incorporated into biomedical device. Earlier researches involved a battery powered and wired interface circuitry to control the IPMC movement [3-4], which could limit its mobility. In addition, it is not practical to be utilized in implantable biomedical device where the battery leakage is hazardous to human health. Wireless powered IPMC actuator eliminates the need for battery might be a solution which potentially advantageous in term of size, flexibility and robustness. Lee et al. [5] reported high frequency (9 GHz) microwave powered IPMC actuator using microstrip patch antenna patterned on the EAP material. This approach, despite eliminating battery involvement, high frequency microwave transfer scheme is sensitive to the environments change, such as temperature and humidity. High frequency microwave also poses practical issue for implantable purpose. Wireless radio-frequency (RF) magnetic field power transfer scheme might be a solution.
which potentially advantageous in terms of power consumption and stability. K. Abdelnour et al. [6] reported a resonant coupling as the wireless powering scheme incorporated with a bridge rectifier to convert AC signal into DC to control the IPMC. This RLC receiver coil and bridge rectifying circuit, nonetheless, tends to have relatively large size and dimension. Planar based receiver and rectifier circuit could be a promising approach to address the mentioned drawback. This paper reports a wireless radio frequency (RF) magnetic field controlled IPMC cantilever actuator using planar LC receiver circuit. Resonant coupling is selected as the wireless powering scheme due to its endearing performance, such as long wireless transmission distance, as discussed in [7]. The planar based LC receiver circuit and DC rectifier circuit are fabricated using double sided polyimide copper sheets. The wireless responses of the developed IPMC actuator are experimentally characterized.

2. Design and Working Principle

| Parameter | Representation | Value     | Parameter | Representation | Value     |
|-----------|----------------|-----------|-----------|----------------|-----------|
| $V_s$     | AC Voltage input | 15 V_ac   | $C_1$     | Source capacitor | 23.053 pF |
| $L_1$     | Source loop inductance | 2503.176 nH | $C_2$     | Load capacitor   | 27.85 pF  |
| $L_2$     | Source resonator inductance | 1791.462 nH | $C_3$     | Rectifier capacitor | 220 μF  |
| $L_3$     | Load resonator inductance | 1482.834 nH | $D_1$     | Rectifier diode  | n/a       |
| $L_4$     | Load loop inductance | 151.962 nH | $D_2$     | Rectifier diode  | n/a       |

Table 1. Parameter Of The System

Figure 1. (a) Design and working principle of the wireless powered IPMC actuator and (b) Lumped mass model of the resonant coupling system.

The wireless power transfer system utilizes a planar inductor-capacitor (LC) circuit serves as the transmitter and receiver to power the IPMC actuator, as shown in Fig. 1 (a). The resonant coupling system consists of a LC transmitter and receiver circuits that are designed to have two rectangular-spiral coils as the resonator and source or load loops, respectively with integrated capacitor to form LC tank. The load loop induces AC voltage when it is exposed to the external magnetic field generated by the LC transmitter circuit when the field frequency matches its resonant frequency. To demonstrate IPMC cantilever in unimorph motion, the LC tank is coupled with a class- D half wave rectifier circuit [8]. The lumped mass model representing the resonant coupling system is shown in Fig. 1 (b). In this figure, $L_1$ and $L_2$ form the transmitter circuit and $L_3$ and $L_4$ form the receiver circuit. The AC voltage from the LC receiver is converted into DC voltage via rectifier circuit to activate the IPMC cantilever. Table 1 shows the parameter representation and the calculated components values using equation 1.
The self-inductance of each loop in the LC circuits were calculated using modified Wheeler Formula [9] defined as

\[ L_{mw} = K_1 \mu_o \left( n^2 d_{avg} / (1 + K_2 \rho) \right) \]  

(1)

where \( K_1 \) and \( K_2 \) are layout dependent, \( n \) is number of turn, \( d_{avg} \) is average diameter within the planar coil and \( \mu_o \) is the permeability in air. Resonator in the transmitter and receiver are resonantly coupled and the resonant frequency is achieved by tuning the shunting capacitor \( C_1 \) and \( C_2 \),

\[ 1/L_2 C_1 \approx 1/L_3 C_2 \]  

(2)

The diameter of resonator coil in transmitter circuit (100 mm) is designed larger than the receiver circuit (13 mm) in order to enhance the transmission distance as discussed in [10]. The distance of transmission, \( D \) is estimated through

\[ D = \sqrt{D_{o,Tx} \times D_{o,Rx}} \]  

(3)

where \( D_{o,Tx} \) is diameter of the transmitting resonator and \( D_{o,Rx} \) is diameter of the receiving resonator. The resonant frequency of the system is designed at 25 MHz with the maximum transfer distance of ~5 cm. The IPMC cantilever bends at resonant frequency (maximum voltage) due to the migration of mobile cations to the cathode in the ion exchange membrane. This operation creates a pressure across the cantilever and causes the IPMC to bend in the anode direction [11].

3. Fabrication

The planar LC circuit was formed by using double sided copper-clad polyimide (PI) film (AP7156E, DuPont, USA) via dry film photolithography process. First, both top and bottom sides of the LC receiver circuit (consists of two rectangular-spiral coils as the resonator and load loop and a capacitor plate) were fabricated by wet etching the copper-clad layers. Next, to connect the top and bottom Cu side of the PI film, via contacts were etched at the PI film and covered with silver conducting epoxy. The fabricated LC receiver circuit is illustrated in Fig. 2 (a). A 0.11 mm thick DC rectifier circuit was fabricated using the similar method with bonded power electronic components to form class-D half wave rectifier circuit. To fabricate the IPMC actuator, a 183 \( \mu \)m thick Nafion 117 (Dupond, USA) and was cut into T-shape to form 8 mm long cantilever. Next, silver was chemically deposited at the photolithography-patterned Nafion 117 through silver mirror method [12] to form different polarity electrode pads. The chemical electroless plating might induce high internal stress to the IPMC and result to serious curliness. Therefore, low temperature annealing was performed to remove the internal stress. The IPMC cantilever was placed in a vacuum drying oven and heated at 140 °C for 3 hours. Fig. 2 (b) shows the IPMC cantilever after the annealing process. The IPMC cantilever is flatten due to the removal of internal stress. Finally, the developed IPMC cantilever was bonded to the DC rectifier circuit using silver conducting epoxy.

![Figure 2](image-url)
4. Experimental Result And Discussion
To demonstrate the proposed wireless power cantilever IPMC, the experimental setup in Fig. 3 (a) and (b) were constructed. A square wave function generator (SFG-830, GW Instek, Taiwan) and an op-amp amplifier (output power of 0.6 W) were implemented to produce magnetic field with the LC transmitter circuit connected. An oscilloscope (MDS1102CA, Matrix, China) was used to determine the electrical response of the LC receiver circuit and DC rectifier circuit. The setup also involved a laser displacement sensor (CD5-85, Optex, Japan) to characterize the cantilever tip displacement. The constructed wireless power transfer system was designed to be operated at \( \approx 25 \) MHz, based on the tunable value shown in Table 1. To features biocompatibility of the developed LC receiver circuit, the LC receiver circuit was encapsulated with a layer of 1 mm thick polydimethylsiloxane (PDMS) material. Fig. 4 (a) illustrates the induced DC output voltage at the DC rectifier circuit with the LC receiver circuit without PDMS encapsulation (direct exposed to air) and with PDMS encapsulation. A maximum DC output voltage of \( \approx 2.3 \) V\(_{dc}\) was noted in both cases at the same resonant frequency, \( \approx 25 \) MHz. This shows that the PDMS medium do not cause significant change in the device’s resonant frequency. In addition, it also shows a good agreement with the theoretical calculated value, where a maximum output voltage is attained at resonant frequency of 25 MHz. To study the IPMC cantilever deflection profile, the laser displacement sensor was located above the tip of IPMC cantilever, as shown in Fig. 3 (b), to measure the tip displacement of the IPMC cantilever. The result presented in Fig. 4 (b) shows the temporal response of the IPMC cantilever activated in wireless ON-OFF cycle: 10 seconds ON, 10 seconds OFF with \( \approx 3 \) V\(_{dc}\) output voltage. As can be seen in Fig 4 (b), 66 m of cantilever displacement is measured at the 10th second of the ON activation. The cantilever deflection, however, experiences slight increase to 70 m at the end of OFF cycle. To verify this deflection behavior, the voltage profile of the LC receiver circuit was examined. The voltage slightly decreases after the 3rd second at the ON cycle due to the capacitive effect in the DC rectifier circuit. On the other hand, the voltage decreases abruptly at the OFF cycle to \( \approx 2 \) V\(_{dc}\). As discussed in [13], IPMC working voltage ranges from 1 V\(_{dc}\) to 3 V\(_{dc}\). Therefore, the IPMC cantilever will have slight increase at the OFF cycle. IPMC cantilever will remain at its end position if no voltage is induced.

Figure 3. Experimental setup: (a) transmitter and receiver setup and (b) block diagram of whole setup.
5. Conclusion
In this research, a wireless RF magnetic field powered IPMC cantilever has been designed, fabricated and demonstrated. Resonant coupling has been selected as the wireless powering scheme. The planar based LC receiver circuit and DC rectifier circuit have been constructed to miniaturize the size of the whole antenna. The wireless coupling effect of the developed LC receiver circuit with PDMS encapsulated was examined and analyzed. The developed wireless RF magnetic field successfully activated the fabricated IPMC cantilever with a RF power 0.6 W at DC output voltage of ~3 Vdc. Future works will encompass the optimization of the LC receiver circuit design and fabrication procedure for miniaturization, and to use lower loss wireless transfer system to increase the power transfer efficiency.

Acknowledgment
The authors acknowledge the financial support from university fund, UTARRF Vote No: 6200/CC8 (Project No. IPSR/RMC/UTARRF/2017-C1/C01).

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