

# Electroactive Polymer Actuator for Lens-Drive Unit in Auto-Focus Compact Camera Module

Hyung-Kun Lee, Nak-Jin Choi, Sunkyung Jung, Kang-Ho Park, Hewon Jung, Jae-Kyu Shim, Jae-Wook Ryu, and Jongdae Kim

We propose a lens-drive unit composed of an ionic polymer-metal composite (IPMC) for an auto-focus compact camera module in cellular phones to solve the power consumption problem of voice coil motors which are widely used in commercial products. In this research, an IPMC incorporated into a lens-drive unit is designed to implement a large displacement in low-power consumption by using an anisotropic plasma treatment. Experimental results show that a camera module containing IPMCs can control and maintain the position of the lens by using proportional integral derivative control with a photo-reflective position sensor despite the non-linear actuation behavior of IPMCs. We demonstrate that the fabrication and commercialization of a lens actuator that has a large displacement and low power consumption using IPMCs is possible in the near future.

**Keywords:** Ionic polymer-metal composite (IPMC), lens-drive unit, compact camera module (CCM), power consumption.

## I. Introduction

“Convergence” refers to the synergistic combination of research areas that are settling down into their own fields, such as information technology (IT), nanotechnology (NT), and biotechnology (BT). Convergences are now expected to overcome current technological limits through quantum jumps, combining research fields synergistically. For example, IT has been profiting by producing prominent items in telecommunications, electronics, computer technology, and so on. IT is generating technological breakthroughs by combining with NT to produce miniaturized components and improve computational speed or low power consumption properties [1], [2].

Our main goal is to solve the power-consumption problem of auto-focus (AF) compact camera modules (CCMs) in cellular phones by adopting electroactive polymers (EAPs) to replace the voice-coil-motor (VCM), which consumes a significant amount of electricity for auto-focusing. EAPs are smart materials that can respond to an external stimulus, such as an applied voltage. Therefore, EAPs have been considered one of the candidates that can be integrated into the actuators or motors of mobile instruments and ubiquitous modules due to their light weight, pliability, and low-power consumption [3]. EAPs can be divided into two categories depending on their activation mechanism [4]. One category is *field-activated* EAPs, which are known to have the advantage of a high response speed ( $<10^{-3}$  s) but require a high voltage (100 V/ $\mu\text{m}$ ). The required high voltage is not suitable for mobile instruments or ubiquitous modules. The other category is *ionic* EAPs. Ionic EAPs are more suitable than field-activated EAPs because ionic EAPs are driven under several applied voltages.

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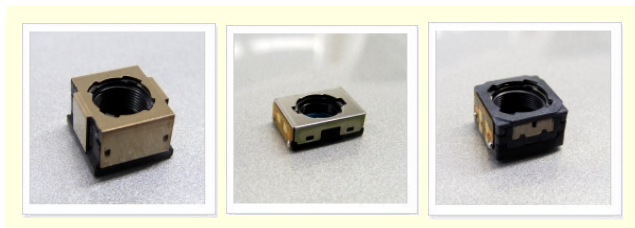


Fig. 1. VCM actuators for mobile AF cameras.

These days, lens-drive units in AF actuators have been generally adopting mega-pixel CCMs in cellular phone camera applications. There are many kinds of AF actuators in mobile phone cameras, such as step-motors, VCMs, piezo motors, and shape memory alloys. Among these actuator types, the VCM type shown in Fig. 1 has been most popular due to its compactness, low cost, and high productivity characteristics. However, along with these advantages, there is a very big disadvantage in the VCM type actuator. Current consumption in a hold-position state has been the biggest issue to solve in CCM manufacturing.

Based on this issue, EAP actuators that incur low production costs and show small current consumption characteristics have been distinguished among the actuators of the cellular phone industry.

Ionic polymer-metal composite (IPMC) is one of the ionic EAPs that we adopt to solve the power-consumption issue in CCMs. Metals such as platinum or gold typically form composite materials with ionic polymer film, typically Nafion, to play the roles of electrodes. In early research on IPMCs, their fabrication methods and most of their concepts were devised and introduced by Oguro [5] and Shahinpoor [6]. In their works, many materials have been investigated as electrode materials and deposited layers, and the effect on the types of electrolytes and mobile cations in the IPMC has been investigated. Leo contributed to the development of IPMCs containing ionic liquids that are not affected by humidity or electrolysis under an applied voltage [7], [8]. Kim also contributed to the fabrication and applications of various types of IPMCs containing CNT and metal particles [9], [10]. Nemat-Nasser studied the behavior of IPMCs with various cations and solvents [11], [12]. He contributed to the establishment of a mechanism for IPMC actuations.

In addition to these pioneering works on IPMCs, we studied a film roughening method to improve the response speed and displacement of IPMC actuation. We presented an anisotropic plasma etching technique by reactive ion etcher as a new pre-treatment method and have already found that the new technique provides a large displacement to a fabricated IPMC in the presence of a low applied voltage [13]. Based on previous research, we report in this study on the fabrication of

an AF compact camera module containing IPMCs as lens-drive units and the low power consumption property of the resulting camera module using IPMCs manufactured from an anisotropic pretreatment. We found that the lens-drive unit demonstrated a power consumption that was less than 16% of the power consumption of the conventional lens-drive units composed of VCMs.

## II. Experiments

### 1. Fabrication of IPMCs Containing Pt Electrodes

Nafion 1110 (DuPont Co.), a perfluorosulfonic acid membrane with 254  $\mu\text{m}$  thickness, was used to produce the large blocking force that is needed to make a lens in a camera module move with a fast response. The IPMCs were fabricated following the procedure reported by Millet and others, except for the surface roughening step [14].

The surface roughening step is required to improve the adhesion of a metal electrode on a Nafion film. The conventional methods of roughening Nafion, such as sandblasting and sandpaper, have been used. However, these cannot provide a surface with homogeneous roughness and result in unpredictable properties in the produced IPMCs due to the non-uniformity of their surfaces. Furthermore, these methods cannot provide patterned roughness on a Nafion surface that is expected to be effective in the facile bending of IPMC actuation. Therefore, we developed a plasma etching technique which is a new concept of polymer roughening using a shadow mask and can be compatible with semiconductor processes [13]. Plasma etching has been used in semiconductor processes for uniform surface treatment. We found that a Nafion surface treated by  $\text{O}_2$  plasma is uniformly covered by nano-embossments. Because the nano-embossments were generated by plasma etching, the depth of the embossments were affected by the etching time and etching power. We investigated an etching condition for Nafion that can be utilized for manufacturing IPMCs.

After setting the etching conditions for Nafion, anisotropically etched Nafion was fabricated using oxygen plasma at a 50 sccm flow rate, 240 W, and 50 mTorr for 1 min under a shadow mask. The shadow mask has a pattern of equally distributed stripes with various widths and various spacings. The resulting Nafion has trenches on the surface, which perform the role of increasing the surface area and helping the IPMC bend more easily. Therefore, we tried to measure and analyze the surface resistance, bending displacement, and driving force of the resulting IPMC from the anisotropically etched Nafion in order to find the optimum anisotropic pattern for an IPMC. Consecutive isotropic

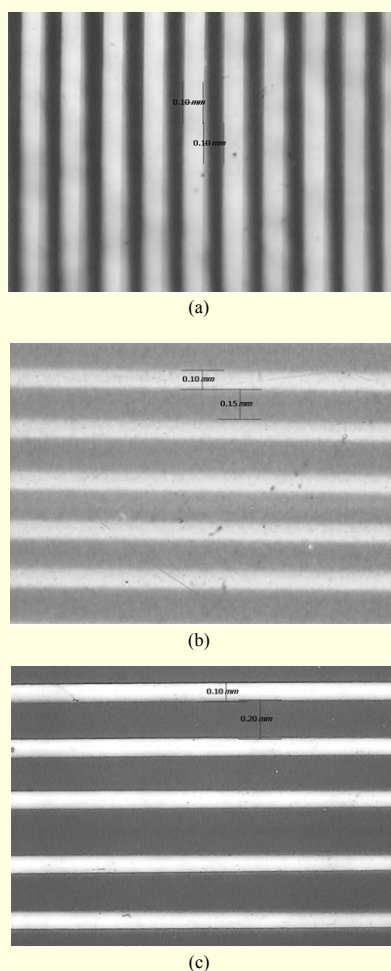
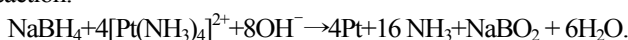


Fig. 2. Optical images of an anisotropic pattern on Nafion film after plasma etching using a shadow mask containing (a) 100  $\mu\text{m}/100 \mu\text{m}$ , (b) 150  $\mu\text{m}/100 \mu\text{m}$ , and (c) 200  $\mu\text{m}/100 \mu\text{m}$  as a slit/space.

etchings without a shadow mask were performed on the Nafion surface. Various shadow masks were used for anisotropic etching of the Nafion film, and Fig. 2 shows optical images of the resulting Nafion surface containing an anisotropic roughened surface. Dark areas in the images are trenches generated by slit openings of the shadow mask, and bright areas are the parts blocked by spaces between the slits in the shadow mask during the anisotropic etching.

In the ion exchange step (adsorption), Pt complex ( $[\text{Pt}(\text{NH}_3)_4]^{2+}$ ) was substituted for  $\text{H}^+$  of the sulfonic acid group ( $-\text{SO}_3\text{H}$ ) located at the side chains of perfluorosulfonic polymer.

In the first plating step (reduction), the adsorbed Pt complex was reduced to the platinum metal by the following chemical reaction:



Here, the first plating process was carried out 4 times in order to increase the blocking force and displacement of the IPMC.

The thickness of the Pt plated on both sides of the film is approximately 20  $\mu\text{m}$  after 4 instances of the reduction process. The solvent used in the entire fabrication process was a mixture of water and ethanol in a 3:1 volume ratio. In the second plating step (surface electroding), an additional platinum layer was introduced on the Nafion surface. Next, in the ion exchange step,  $\text{Li}^+$  ions were substituted for  $\text{H}^+$  ions. Finally, in the ionic liquid substitution stage, the obtained IPMC containing water/ethanol as a solvent was dried in a vacuum at 110°C for 12 h and consecutively immersed in a mixed solvent of 1-ethyl-3-methylimidazolium trifluoromethane sulfonate (EMIM-TfO) and methanol in a 2:1 weight ratio. After that, the residual methanol was removed by vacuum drying at 110°C for 3 h. The substitution of ionic liquid into the IPMC was monitored by analyzing the composition ratio of metal, polymer, and ionic liquid using thermo gravimetric analysis under a nitrogen atmosphere by heating up to 800°C.

## 2. Fabrication of IPMCs Containing Cu/Ni Electrodes

When a lens-drive unit needs a strong blocking force, electroplating of copper can be carried out to fabricate a Cu electrode of the IPMC on Nafion instead of a Pt electrode. The copper plating solution consists of  $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$  (20 g), sulfuric acid (7.5 g), and distilled water (100 g). Cu plating was investigated by varying the plating time from 9 s to 120 s. Also, a nickel plating solution consists of  $\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$  (15 g),  $\text{NH}_4\text{Cl}$  (1.5 g),  $\text{H}_3\text{BO}_3$  (1.5 g), and distilled water (100 g) [15]. The pH of the Ni plating solution was adjusted within a pH range of 3 to 4. Ni plating was investigated by varying the plating time from 7 s to 100 s. In the electroplating, plate or mesh (40 mesh) type Cu and Ni counter electrodes were used.

## 3. Measurement of IPMC Actuation

The test specimens were cut out in rectangular strips with a size of 8 mm  $\times$  3 mm. The thickness of all specimens with metal electrodes was measured as approximately 280  $\mu\text{m}$  using a micrometer with deviations of less than 20  $\mu\text{m}$ . The bending characteristics of the IPMC were measured using a laser displacement meter (LK-G30, KEYENCE), and the blocking forces produced by IPMC actuators were monitored using a load cell (PW4M-300G, CASKOREA Co.). Actuations of the IPMC were driven by a PC LabVIEW DAC-board (PCI6229, NI Co.) with an external signal with an amplitude of 3 V and a frequency of 0.1 Hz.

## 4. Camera Module Fabrication

The lens-drive unit for an AF compact camera module was designed to have dimensions of 18 mm  $\times$  13 mm  $\times$  6.1 mm.

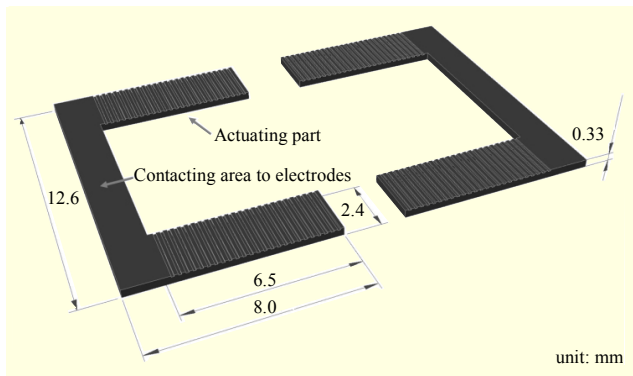


Fig. 3. Layout of IPMC actuator incorporated into compact camera module.

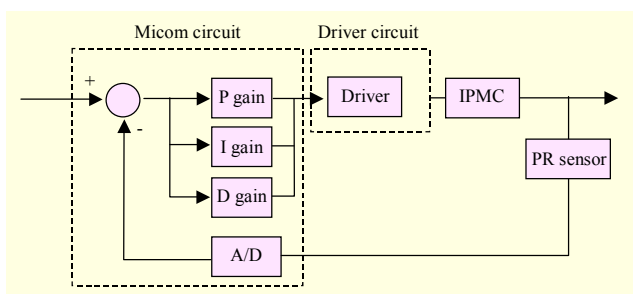


Fig. 4. Displacement feedback system used in a lens-drive unit on an AF actuator.

The working voltage of the resulting lens-drive unit was 4 V, and the full stroke was 250  $\mu\text{m}$ , which is required in order to take a shot of an object 10 cm away using a cell phone.

The layout of the IPMC actuator design is shown in Fig. 3, where 4 actuating parts were integrated. The actuating part has dimensions of 2.4 mm  $\times$  6.5 mm  $\times$  0.33 mm. We incorporated anisotropic patterns on the actuating parts in order to enhance the displacement of IPMCs. Other parts (12.6 mm  $\times$  2.5 mm) were used as contacting areas to electrodes that were located on the top and bottom.

The lens-drive unit consists of leaf springs, a photo-reflective (PR) sensor (NJL5901R-1, JRC, Ltd.), and IPMCs that lift the lens up and down according to the command of the microprocessor through I<sup>2</sup>C communication. The leaf springs are located at the top and bottom of the camera module's guided lens moving at the optical axis, and a PR sensor was used for the displacement feedback system shown in Fig. 4 because of the non-linear behavior of IPMC actuation characteristics.

### III. Results and Discussion

#### 1. Characterization of IPMC Actuation Behavior

Nafion film was etched for various etching times in a plasma etcher under O<sub>2</sub> plasma at a 50 sccm flow rate, 120 W, and

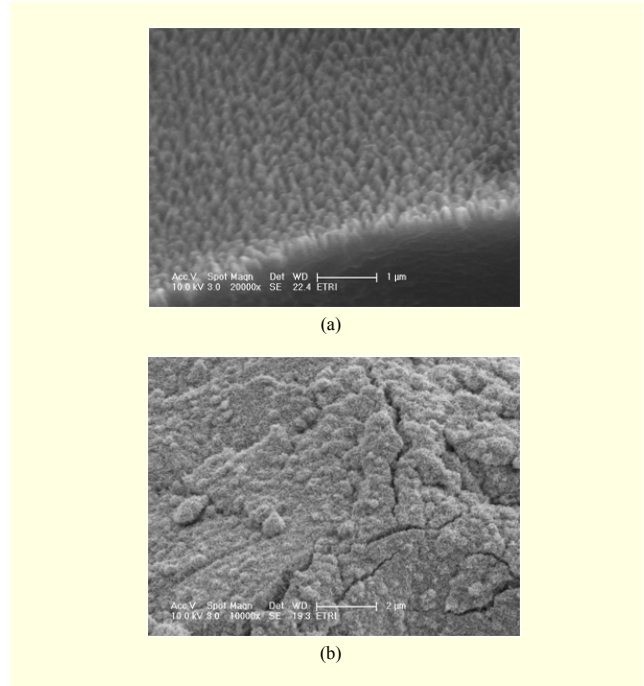


Fig. 5. SEM images of Nafion surfaces etched by (a) plasma etching and (b) sandblasting.

50 mTorr. An SEM image of the surface morphology after plasma treatment for 1 min is shown in Fig. 5(a).

The surfaces treated by the plasma etching method showed a very uniform roughness. However, the surface roughened by the sandblasting method was found to be non-uniform as can be seen in Fig. 5(b). Also, the etched depth from the surface was relatively increased according to the treatment time in the etcher. The etching rate of Nafion film according to etching time was found to be 0.33  $\mu\text{m}/\text{min}$ . When we measured the displacement and blocking force of the resulting IPMCs from various Nafion films etched using various etching times from 20 s to 6 min, we found that the IPMC from Nafion etched for 1 min showed the best result compared to other etching conditions.

Nafion film was etched using slits and spaces of various sizes of the shadow mask in the plasma etcher. The driving properties (displacements and blocking force) of the IPMC in relation to the shadow mask patterns used are shown in Fig. 6 and Table 1. The IPMC from Nafion etched under a shadow mask with a 200  $\mu\text{m}$  slit and 100  $\mu\text{m}$  space showed the best performance in terms of displacement, which was enhanced by about 30% compared to that of a reference sample prepared from Nafion etched isotropically. On the contrary, we could not find any relationship between anisotropic patterns and blocking force of IPMCs. The testing results from different treatment processing on anisotropic plasma etching will be reported elsewhere in detail.



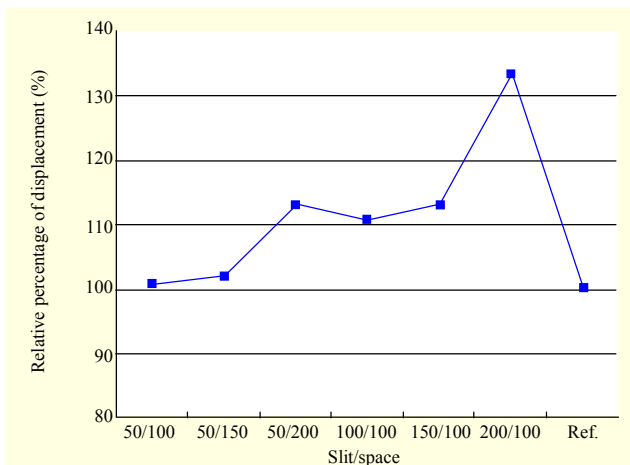


Fig. 6. Displacement of IPMCs from Nafion etched under shadow masks containing different slit/space patterns.

Table 1. Displacement and blocking force of IPMCs depending on anisotropic processing.

Sample (slit/space)	Displacement ( $\mu\text{m}$ )	Blocking force (mgf)
50/100	280	236
50/150	284	268
50/200	314	252
100/100	308	193
150/100	314	226
200/100	370	210
Reference	278	248

## 2. Camera Module Characterization

Many researchers have tried to make an AF camera module using a polymer actuator that can be used in mobile instruments [16]–[18]. However, exact position control is difficult to achieve due to the non-linear motion and back relaxation of IPMCs [19], [20]. In particular, back relaxation is the biggest problem to solve for mechanical control of a lens-drive unit.

We fabricated a camera module to confirm the feasibility test of an IPMC for mobile phones. Each part of the camera module, including the polymer actuator, was packaged as shown in Fig. 7. Top and bottom springs were used to prevent lens tilting because the fabricated IPMC characteristics are not identical to each other. Detailed parts are shown in Fig. 7(a). An input voltage ( $\pm 4$  V) through the top and bottom electrodes was applied to the IPMC. The IPMC is 3 mm in width and 8 mm in length including the contacting area ( $3 \text{ mm} \times 2 \text{ mm}$ ) to the top and bottom electrodes.

The lens of the camera module was controlled by acquiring

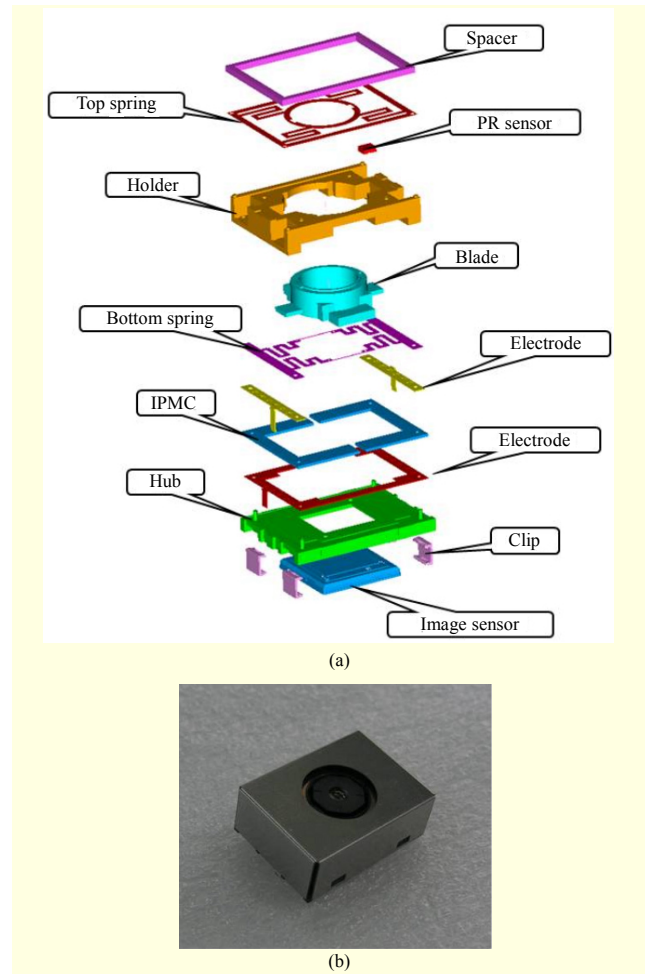


Fig. 7. (a) Detailed parts of a compact camera module containing IPMCs as a lens-drive unit and (b) an assembled compact camera module.

the lens position using a PR sensor and applying proportional integral derivative (PID) control. The IPMC has been notorious for its non-linear actuation behavior due to a back-relaxation phenomenon from electro-osmosis. The PR sensor is incorporated to overcome the non-linear motion and back relaxation of IPMCs. A microprocessor instructs the driving distance of the IPMC using output data calculated from the PID control. Based on the PID control coupled with the PR sensor, the lens position can be correctly controlled.

Throughout this research, we want to confirm that the IPMC demonstrates good performance which is satisfactory for camera modules. Conventional camera modules acquire 10 images moving approximately  $250 \mu\text{m}$ , determine the best of the obtained images in preview mode, and focus on an object using a driving lens in order to take the optimal image while in AF mode. A feasibility test of a camera module using six steps is shown in Fig. 8, where the Y axis is the voltage value of the PR sensor which is correlated with the lens position from the

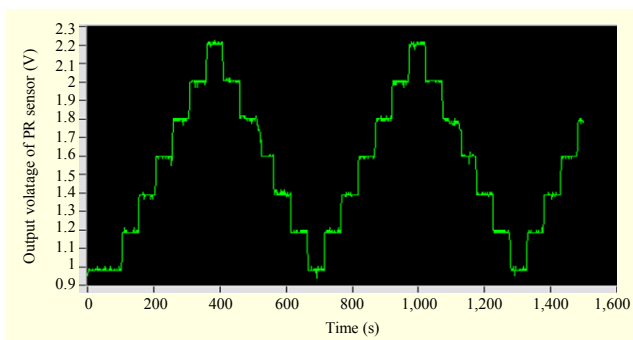


Fig. 8. Lens movement experiment of a lens-drive unit containing IPMCs in an AF actuator.

Table 2. Comparison of power consumption between lens-drive unit using an IPMC and VCM.

IPMC AF actuator		VCM AF actuator	
Actuation distance ( $\mu\text{m}$ )	Consumed power (mW)	Actuation distance ( $\mu\text{m}$ )	Consumed power (mW)
35	0.8	50	7.7
70	5.0	100	30.7
95	15.1	150	69.1
160	22.7	200	122.9
250	30.7	250	192

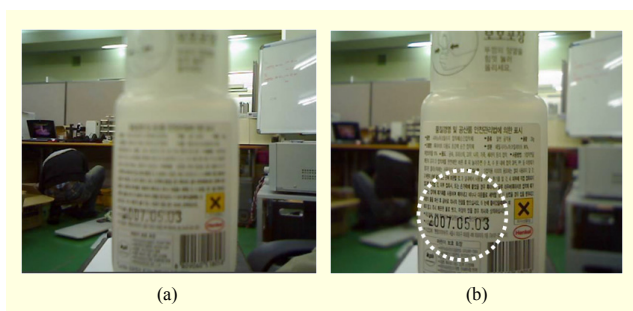


Fig. 9. Focusing on object (a) at an infinite distance and (b) 15 cm away from the camera module.

bottom of the camera module, and the  $X$  axis is the operation time. The camera module moves using the IPMC with applied voltage and maintains the lens position for 20 s before moving to the next step. We confirmed that the moving time is very short and that the camera module can maintain the level of the lens position. The applied DC voltage was  $\pm 4$  V and the consumed power of the camera module was under 50 mW on average. Most interestingly, we found that a current in the range of several tens of mA only was consumed at the starting moment of driving the IPMC, which is very important because the VCM in a current CCM continuously consumes current for this function. In this result, we found that the IPMCs demonstrated an advantage in terms of power consumption

compared to the VCM.

Table 2 shows the power consumption for an IPMC AF actuator and a VCM AF actuator according to the actuation distance. It shows that the IPMC AF actuator consumes about 16% power relative to the VCM.

Figure 9 shows the AF experiments of this lens-drive unit using IPMCs. When the lens-drive unit focuses on an object at an infinite distance, the background image looks vivid as can be seen in Fig. 9(a). On the contrary, Fig. 9(b) shows the macro focused image when the lens moves into focus on an object 15 cm away from the camera module. To capture the macro image marked with a dotted circle, the lens must be moved to 200  $\mu\text{m}$  from the initial position. The letters in the macro image are clearly seen, which proves that the IPMC AF actuator operates very well.

## IV. Conclusion

An IPMC for a lens actuator was made to implement a fast bending speed and large displacement under low power by using an anisotropic plasma treatment. In particular, we fabricated a camera module actuated by IPMCs for a mobile phone. The camera module can control and maintain the position of the lens by using proportional integral derivative control with a photo-reflective position sensor that is introduced to overcome the non-linear drive characteristics of IPMCs. We proved that the fabrication and commercialization of a lens actuator that has a large displacement and low power consumption using IPMCs will be possible in the near future.

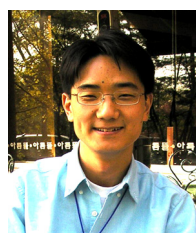
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