# LARGE-DISPLACEMENT ELECTROMAGNETIC ACTUATORS USING THE MEANDER SPRINGS PARTIALLY EXPOSED TO MAGNETIC FIELD

**Dae Geon Seo*, Won Han, and Young-Ho Cho**
Digital Nanolocomotion Center, Department of Bio and Brain Engineering, KAIST,
Daejeon, Republic of Korea
*Presenting Author: nanosys@kaist.ac.kr

**Abstract:** We present the design, fabrication and test of a large-displacement electromagnetic actuator using the meander springs, exposed partially to magnetic field. We compare two prototypes including the conventional prototype F with the meander springs exposed fully to magnetic field and the present prototype P with the meander springs exposed partially to magnetic field. In the experimental study, the amplitude of the prototype P is measured as 30.49±0.36μm at the 40mA square input current of 5Hz, while the amplitude of prototype F is measured as 26.02±0.65μm. The amplitude of the prototype P is 17.2% larger than that of the prototype F, verifying the effect of partial exposure of the meander springs to magnetic field. Therefore, we experimentally demonstrate the large-displacement actuation performance of the present actuator using the partial exposure of the meander springs to magnetic field.

**Keywords:** Meander Spring, Electromagnetic Actuator, Large-displacement Actuator

## INTRODUCTION

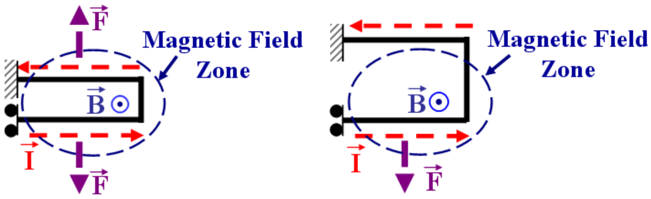
In the areas of nano/micro electromechanical systems (N/MEMS), the electromagnetic actuators for optical communication applications are required to produce a large-displacement actuation performance. The previous electromagnetic actuators [1-5] using the simple beam springs, designed for optical switches or optical choppers, use a bulky magnet with high magnetic fields to generate a large-displacement actuation range. The meander springs, which can implement relatively low stiffness, are more advantageous in producing a large-displacement actuation performance compared to the simple beam springs within the limited electromagnetic force determined by size and volume of permanent magnets. However, the previous electromagnetic actuators using the conventional meander springs have limited in large-displacement actuation because actuation forces are cancelled each other due to the change of current path under the magnetic field. In this paper, we present the electromagnetic actuators, where following on the meander springs are applied for realization of a large-displacement actuation performance within limited area, and the meander springs are partially exposed to the magnetic field to generate the Lorentz force in the only direction of displacement.

## DESIGN AND ANALYSIS

The electromagnetic actuators suggested in this paper generate Lorentz force, *F*, according to Fleming's left-hand rule [6] in case that electric current, *i*, which flows along the electric pathway created in the meander springs between the perpendicular magnetic field, *B*, running from bottom to top. The Lorentz force, *F*, is given by

$$\vec{F} = \int i d\vec{l} \times \vec{B}. \qquad (1)$$

Figure 1 shows the effect of Lorentz force on the actuation of the spring member depending on full (Fig. 1a) and partial (Fig. 1b) exposure of the meander springs to magnetic field. Compared with the full exposure of meander springs to magnetic field (prototype F), the partial exposure of meander springs to magnetic field (prototype P) generates Lorentz force in only one actuating direction; therefore, increasing effect of the displacement is expected in the electromagnetic actuators where meander springs are applied. The electromagnetic actuators proposed in this paper are composed of one silicon actuator and two ring-type permanent neodymium (NdFeB) magnets with surface magnetic field of 0.1T. Figure 2 shows the structure and design of the present electromagnetic actuators. A semicircular blade within the radius of 1.3mm is connected to two meander springs. Prototype F (Fig. 2a) is designed to fully exposure of meander springs to magnetic field, resulting in generating Lorentz force to both forward direction and backward direction simultaneously. On the contrary, prototype P (Fig. 2b) is designed to partial exposure of meander springs to magnetic field, resulting in generating Lorentz force to the only forward direction.

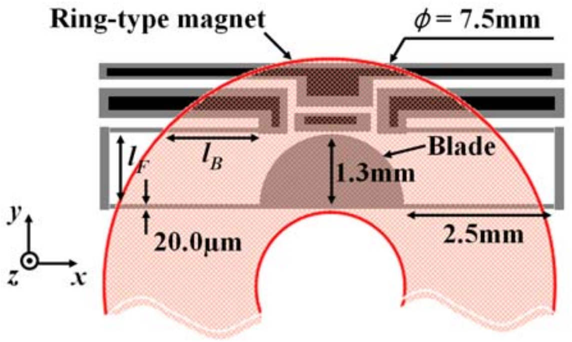



(a) (b)

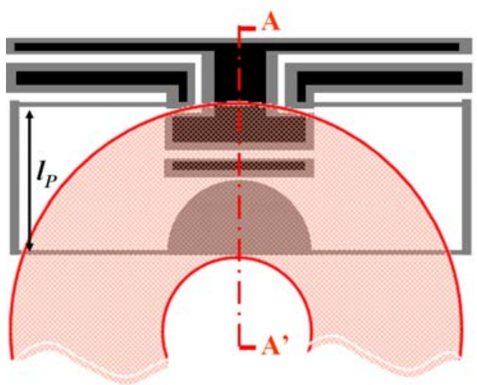
*Figure 1. Lorentz force of the meander springs in the magnetic field: (a) fully exposed to magnetic field; (b) partially exposed to magnetic field;* $\vec{B}$ , $\vec{I}$ , *and* $\vec{F}$ *are magnetic field, input current, and Lorentz force, respectively.*

*Table 1. Designed and measured dimensions of the prototypes shown in Fig. 2*

| Geometric characteristics | Dimensions | |
|---|---|---|
| | Designed | Measured |
| Magnet diameter | 7.5mm | 7.5±0.1mm |
| Aperture diameter | 2.5mm | 2.5±0.1mm |
| Magnet thickness | 1.0mm | 1.0±0.1mm |
| Blade radius | 1.3mm | 1.3±0.1mm |
| Spring width | 20.0μm | 20.0±0.5μm |
| Length of span beam inducing forward magnetic force | 2.5mm | 2.5±0.1mm |
| Length of connector beam in prototype F ($l_F$) | 1.35mm | 1.35±0.1mm |
| Length of connector beam in prototype P ($l_P$) | 2.54mm | 2.54±0.1mm |




(a)




(b)

*Figure 2. Schematic view of the electromagnetic actuators: (a) top view for prototype F; (b) top view for prototype P.*

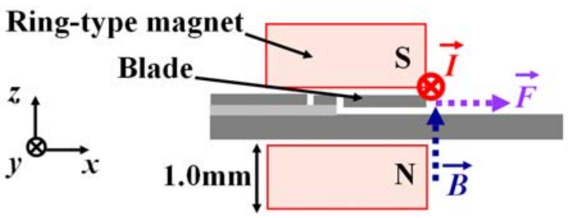



*Figure 3. Cross-section view across A-A' in Fig. 2(b).*

The actuation occurs vertically to x-axis in the direction of current which flows to the meander spring located inside the magnetic field perpendicular to z-axis by the Lorentz force generated in proportion to the amount of the input current as shown in Figure 3. In both prototypes, the length of span beam which generates actuation force was designed to be 2.5mm, considering the permanent neodymium (NdFeB) magnets in the 7.5mm external diameter and the blade within a 1.3mm radius. And the both width and thickness of the meander springs were designed to be 20μm, considering the fabrication safety for deep reactive ion etching (DRIE) process and the thickness of top Si layer for the silicon-on-insulator (SOI) wafer (20/2/500μm) to use. Prototype F, the fully exposure of the meander springs to magnetic field, was designed to have the length of span beam ($l_B$) of 1.45 mm in order to generate force in the opposite direction of actuation; moreover, the length of connector beam ($l_F$) is designed to be 1.35mm. On the other hand, prototype P, the partially exposed structure of the meander spring to magnetic field, was designed to have the length of span beam ($l_B$) of 0mm in order to remove the opposite direction of actuation force; moreover, the length of connector beam ($l_P$) was designed to be 2.54mm. The result of FEM analysis through the COMSOL Multiphysics simulation confirms that the prototype P showing the increase of 12.4~13.0% in amplitude for varing 5Hz square input current from 10 to 40mA compared to the prototype F.

## MICRO FABRICATION PROCESS

The present electromagnetic actuators were fabricated using silicon-on-insulator (SOI) wafers, as illustrated in Fig. 4. The 20μm-thick top silicon of SOI wafers was patterned by deep reactive ion etching (DRIE) process with an etch mask of photo resist (PR) (Fig. 4b and 4c). After DRIE, PR used as etch mask, was removed and each device was seperated by using dicing saw (Fig. 4d). The 2μm-thick buried oxide layer was removed using a buffered oxide etchant (BOE) solution for the release of devices (Fig. 4e). The 500/5000Å-thick Cr/Au were sputtered to formulate electrode (Fig. 4f). Figure 5 shows SEM photographs of the fabricated prototypes, and the measured dimensions are presented in Table 1.

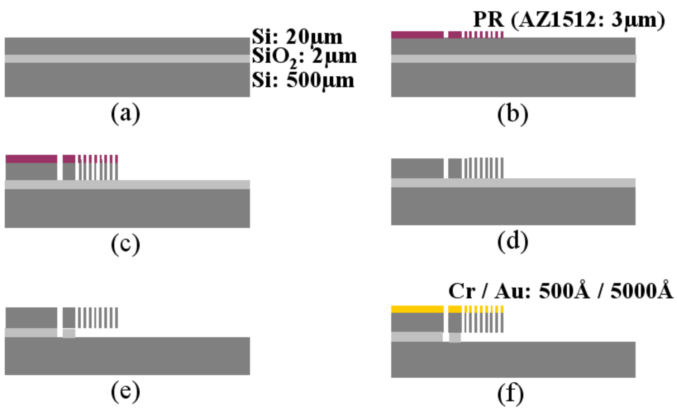
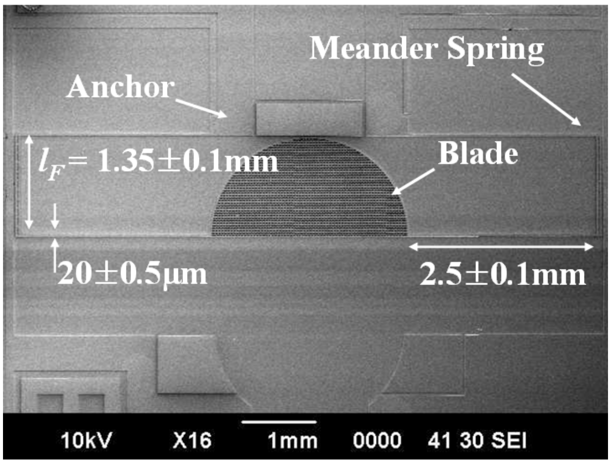
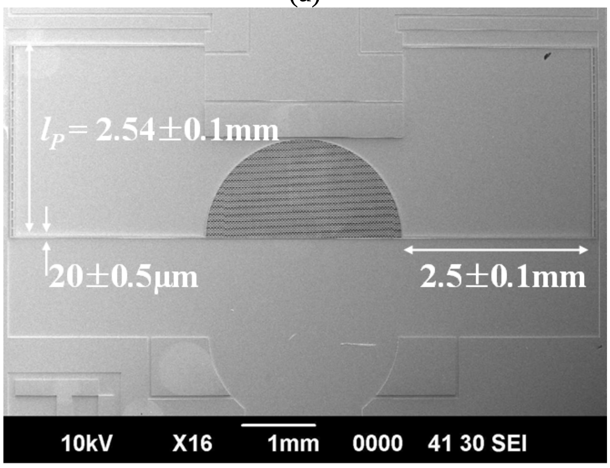



*Figure 4. Fabrication process showing the cross-section of A-A' in Fig. 2 (b): (a) starting SOI wafer; (b) PR patterning; (c) Si DRIE; (d) PR removal & device dicing; (e) shutter release; (f) Cr/Au layer(500Å/5000Å) sputtering for electrode.*




(a)




(b)

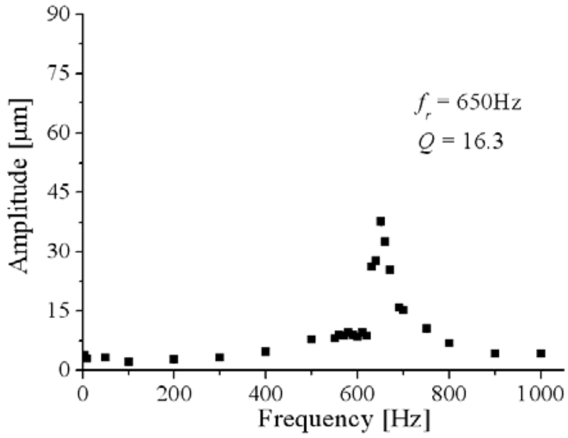
*Figure 5. SEM photograph of the fabricated device: (a) prototype F; (b) prototype P.*

## EXPERIMENTAL RESULTS

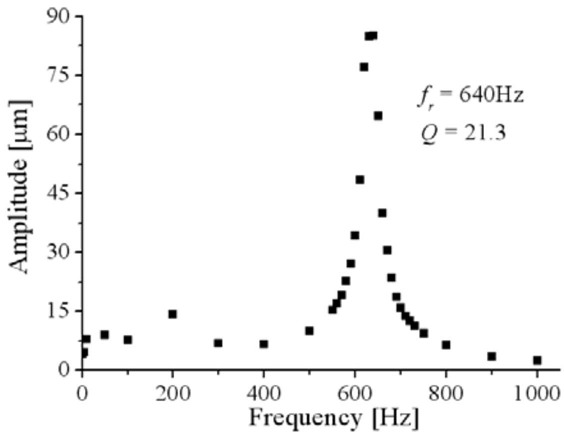
From the fabricated silicon actuator placed between the two ring-type neodymium (NdFeB) permanent magnets, we measured the amplitude of the blade for frequency and time by using a LDV (Laser Doppler Vibrometer) and a signal analyzer. Figure 6 shows the experimental results of the frequency responses from 5Hz to 1kHz at 5mA square input current according to each prototype. In case of prototype F (Fig. 6a), resonant frequency ($f_r$) of 650Hz and Q-factor of 16.3 were measured, and in case of prototype P (Fig. 6b), resonant frequency ($f_r$) of 640Hz and Q-factor of 21.3 were measured. Figure 7 shows the theoretical and experimental amplitude of the prototypes for varing 5Hz square input current from 10 to 40mA, and verified the meander springs were partially exposed to magnetic field (prototype P) is measured as 16.9±1.2% more increase of amplitude than the meander springs were fully exposed to magnetic field (prototype F). Table 2 summarizes the theoretical and experimental amplitude of prototypes at 40mA square input current of 5Hz. In the experimental results, the amplitude of prototype P (30.49±0.36μm) is 17.2% larger than that of the prototype F (26.02±0.65μm).

*Table 2. Amplitude of the prototypes at 40mA square input current of 5Hz*

| Prototypes | Amplitudes | |
|---|---|---|
| | Theoretical | Experimental |
| F | 28.98μm | 26.02±0.65μm |
| P | 32.60μm | 30.49±0.36μm |




(a)




(b)

*Figure 6. Frequency response of the prototypes at 5mA square input current: (a) prototype F; (b) prototype P.*

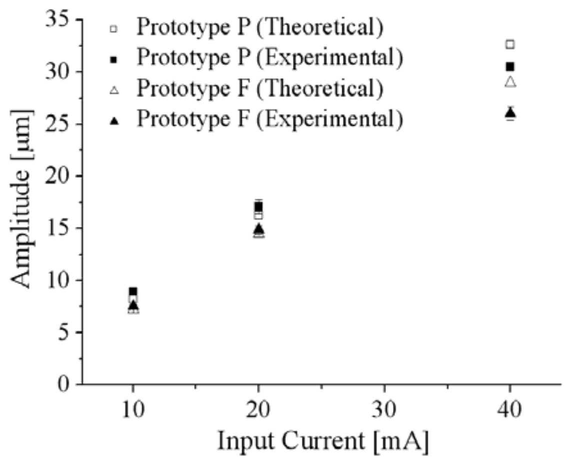



*Figure 7. Amplitude of the prototypes for varying square input current at 5Hz.*

## CONCLUSION

This study has presented the electromagnetic actuators with a partial exposure of the meander springs to magnetic field to generate Lorentz force in the direction of displacement, while applying the meander springs with lower stiffness than previous electromagnetic actuators for large-displacement actuation. We designed and fabricated two prototypes including the conventional prototype F with the meander springs exposed fully to magnetic field and the present prototype P with the meander springs exposed partially to magnetic field. In the experimental study, prototype P is measured as 16.9±1.2% more increase in amplitude than prototype F for varing 5Hz square input current from 10 to 40mA. Therefore, we experimentally demonstrate the large-displacement actuation performance of the present actuator using the partial exposure of the meander springs to magnetic field in small volume ($8 \times 8 \times 3 mm^3$) and low current below 40mA. The proposed electromagnetic actuators can be applied to low-power and large-displacement manipulation of optical information carriers.

## ACKNOWLEDGMENT

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