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A LOW VOLTAGE ELECTROSTATIC MICRO ACTUATOR FOR LARGE OUT-OF-PLANE DISPLACEMENT

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ABSTRACT

An electrostatic actuator is designed to move a 1 mm mirror, 58 μm out of plane at 25 volts. Large out-of-plane displacement is obtained from repulsive forces generated on four sets of comb drive fingers attached to the mirror plate in the middle. The proposed actuator is a customized design of a previous study for low voltage applications. The static modeling of the actuator was performed using a coupled-field finite element model of the actuator, including mechanical and electrical domains. Low voltage operation is achieved by decreasing the finger width and the lateral spacing, which increased the generated repulsive force at a specified voltage in a unit cell of the actuator. Decreasing the lateral spacing also enabled increasing the number of fingers, which could increase the repulsive-force, and consequently the torque and the rotation angles when the vertical gap between moving and fixed fingers is small. However, the redesigned actuator has a lower stiffness compared to the previous design. The actuator is optimized for auto-focusing applications in cell phone cameras that require voltages below 30 Volts for user safety. In the intended auto-focusing module, the actuators do not carry the lens and auto-focusing is obtained by moving the mirror attached to the actuators.

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INTRODUCTION

Micro-mirrors with large out-of-plane displacement find growing applications in many optical devices such as optical filters, high definition projectors, head-up displays, adaptive optics and auto-focusing modules. Actuators used to move the mirrors are thermal, piezoelectric and electrostatic. Electrothermal MEMS mirrors are reported to have large out-of-plane displacement at a very low voltage and low power and are applied for optical coherence tomography [1–7]. The most common type of electrothermal actuators are biomorph actuators, which are made of two materials with different thermal expansion [4]. Sun et al. [4] reported more than 600 μm vertical displacement and ± 30 degrees tilt using 5.5 Volts. However, the speed was relatively low (imaging speed of 2.5 frames/ sec with scanning speed of 320 Hz). A similar design was also used by Wu et al. [3] and the reported resonant frequency for the vertical motion was 0.5 kHz with the thermal response time of 25 ms. Piezoelectric actuators [8] also have been used for out-of-plane displacements and in-plane rotations, with maximum displacement reported as 42 μm at 25 Volts with a low power of 450 μW. The disadvantage of piezoelectric actuators is their complex fabrication process.

In contrast to aforementioned actuation types, electrostatic actuators have easy fabrication, fast speed, and low power, but they require high voltage to operate. There are a number of electrostatic actuators reported with large out-of-plane displacement. Using a lever mechanism, Dagel et al. [9] obtained 27 μm out-of-plane translation with electrostatic actuation. Using orthogonal vertical comb-drive actuators attached to a micro-mirror through mechanical rotation transformers, Milanovic et al. [10] reported out-of-plane displacement of 30 μm at 130 Volts. Large stroke electrostatic actuators using comb-drives driven by repulsive force were studied by He et al. [11–15]. A one millimeter mirror was attached to four sets of electrostatic actuators that were driven by the repulsive force and the generated torque on the fingers. They reported static out of plane translation of the mirror up to 86 μm at 200 Volts [15] using the standard micro-fabrication process of POLYMUMPS.

The contribution of this paper is to redesign the repulsive force actuators introduced by He et al. [15] for low voltage applications. Using the same actuator area, the actuators are designed to produce the same amount of out-of-plane translation at a reduced voltage by decreasing the fingers' width and lateral spacing, increasing the number of fingers, and changing the fingers' direction to the horizontal direction. The redesigned actuator has a lower stiffness compared to the previous design. The intended application of the actuator is in cell phones, which require operation voltages less than 30 Volts. The actuator can be used to move a mirror in an auto-focusing module of a cell phone camera.

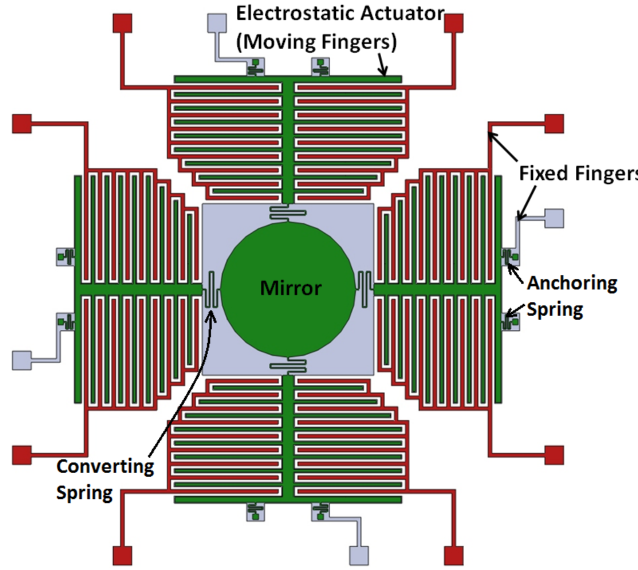

FIGURE 1: Low voltage actuator.

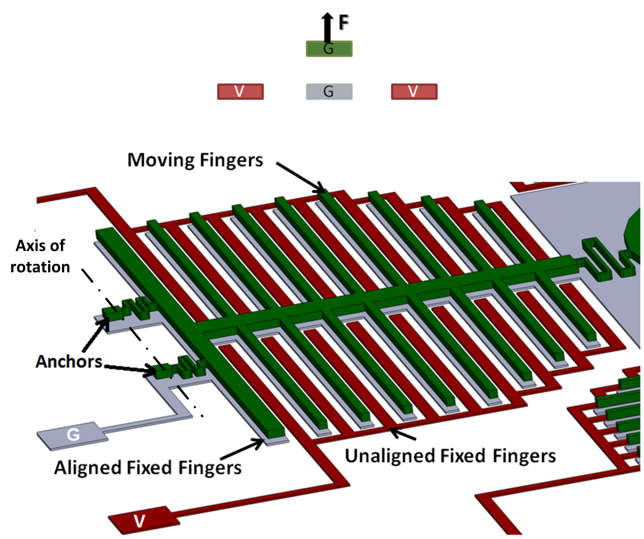

FIGURE 2: Zoomed in part of the actuator.

REPULSIVE FORCE ACTUATOR

The actuator is comprised of four sets of moving fingers (Figure 1) that are anchored to the aligned fixed Fingers (Figure 2) through anchoring springs and are connected to the ground. There are also unaligned fixed fingers (Figure 2) that are connected to voltage. An asymmetric electric field is created between the moving fingers and the fixed fingers in this orientation that generates a force on the moving fingers that pushes the fingers away from the substrate (repulsive force). The repulsive force creates a torque around an axis that passes through the anchors and rotates the fingers' base around the axis of rotation (Figure 2). If the same voltage applies to the four sets of fingers, they generate the same amount of rotation angle that translates the mirror plate out of its plane.

To decrease the voltage consumption by the actuator, the repulsive force actuator [15] is redesigned by considering the design parameters that affect the asymmetric electric field in unit cell of the actuator and thereby increasing the corresponding repulsive force on the actuator. The repulsive-forces were also additionally increased by increasing the number of the fingers in the same actuation area. Among the design parameters, the width of the fingers and lateral spacing were found to be significant according to the analysis in the following sections.

Electric Field and Moving Finger Width

In this section, the effect of the moving finger width is considered on the electric field generated on the moving finger. Figure 3 shows the electric field strength at a unit cell cross section of the moving finger (top finger) and the aligned and unaligned fixed fingers (bottom fingers) for the actuator in reference [15]. In this figure, unaligned fingers have 10 Volts and aligned fingers and moving fingers are connected to the ground. The largest electric field strength was found around the edges of the aligned fixed finger, 35,000 V/m. However, the legend maximum is changed to 1.120 X 10^6 V/m to be consistent with Figure 4.

Careful examination of the electric field distribution reveals that the strength of the electric field is largest at the top corners

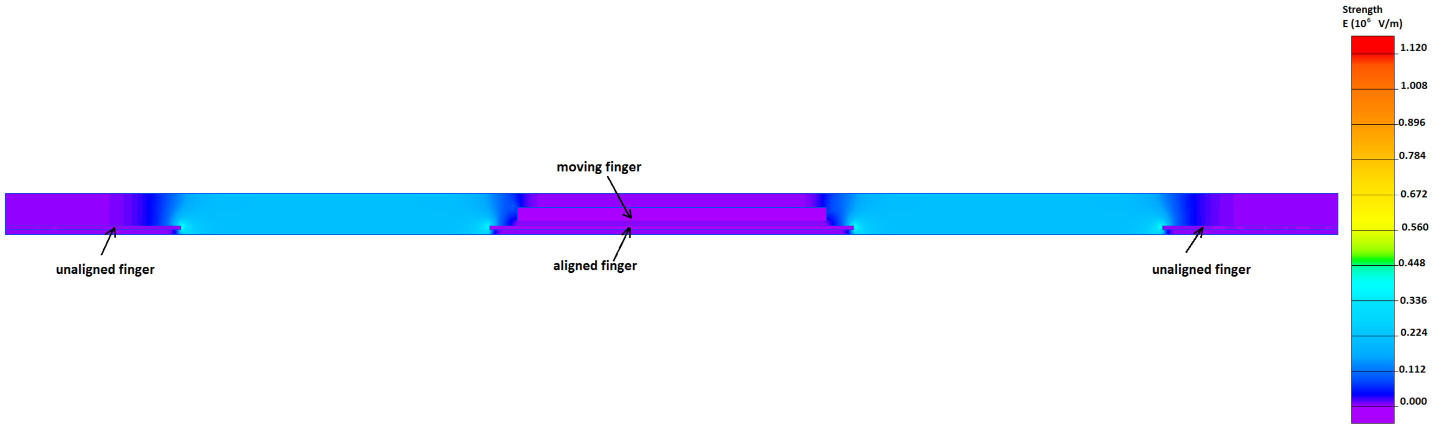

FIGURE 3: Electric field strength at 10 Volts voltage difference between the aligned and unaligned fingers for the actuator designed by He et al. [15] obtained by Quickfield package. The colored figure is provided in the online copy.

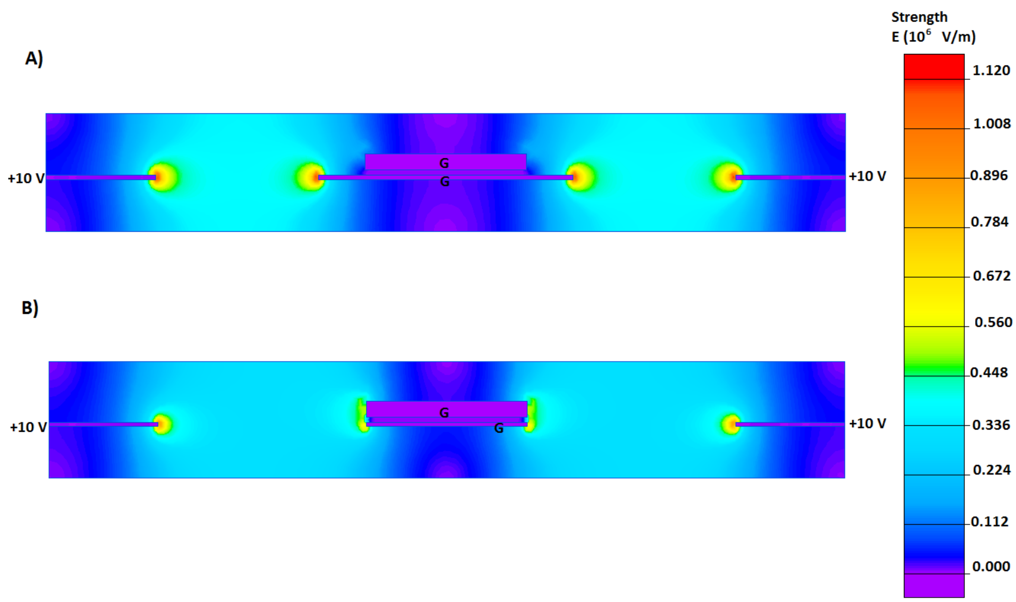

FIGURE 4: Electric field strength at 10 Volts voltage difference between the aligned and unaligned fingers, when the width moving finger is A) smaller than, B) equal to, the width of the aligned fixed finger obtained by Quickfield package

of the moving finger, which creates an asymmetric electric field and a repulsive force (away from the aligned finger) on the moving finger with the magnitude of 0.024 μN (found from Quickfield package in Figure 3). It is also noted that the middle of the moving finger experience small electric field. This means that the moving finger width can be further decreased to increase the electric field strength on the corners and to increase the electrostatic repulsive-force generated on the finger when thr vertical gap is small. Therefore, the moving finger width, the lateral spacing and the fixed finger width were decreased to less than half with the dimensions listed on Table 1. Other dimensions of the actuator can be found in Figure 5. As illustrated in Figure 4 A, it was found that the electric field strength profile and the repulsive force on the moving finger increase in a unit cell of the actuator. The repulsive force on the moving finger (obtained from Quickfiled package analysis) increases from 0.024 μN for reference [15] to 0.307 μN at 10 Volts for reduced finger width and lateral spacing for a small vertical gap.

Electric Field and Aligned Finger Width

Keeping the moving finger width and the spacing constant in the new design, the effect of aligned finger width is also con-

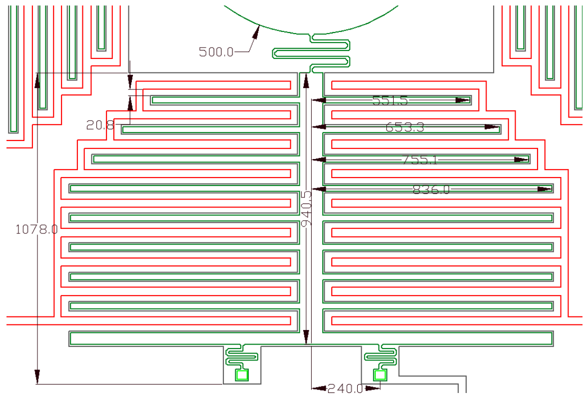

FIGURE 5: low voltage actuator dimensions (μm)

sidered on the electric field. The aligned finger width is reduced to have the same width as the moving finger (Figure 4B). Once the electrodes have the same width, the electric field strength at the corners of the moving fingers is increased as shown in Figure 4B. This increase generates a larger repulsive force and torque on the moving finger, 1.77 μN for equal width configuration compared to 0.307 μN for different width configuration. Larger torque can increase the rotation angle. However, because the intention is to use the PolyMUMPS standard fabrication process, the moving finger (made of ploy 1 layer) has to be narrower than the aligned finger (made of poly 0 layer), for at least 4 μm, to protect the substrate from subsequent etching and to avoid large undesired lateral force due to error in layer alignment in PolyMUMPS. Therefore, the different width configuration is used for the finite element analysis despite its lower repulsive forces.

TABLE 1: ACTUATOR PARAMETERS (μm)

	[15]	Low voltage actuator
Moving finger width	45	20.5
Aligned fixed finger width	53	32.5
Unaligned fixed finger width	51	28
Fixed finger spacing	45	20.75
mirror size	1000	1000
Actuator Area	3424.18	3424.18

Finite Element Model of Low Voltage Actuator

Based on the analysis of the finger width effect of the electric field, the actuator is redesigned to have fingers and finger spacing reduced to less than half of the original actuator [15] to produce larger repulsive-force at the same voltage in the range of small vertical gaps. Using the same actuation area, the actuator is composed of four sets of fingers on top, bottom, left and right of the mirror plate. The orientation of the fingers was also changed to horizontal direction (Figure 6).

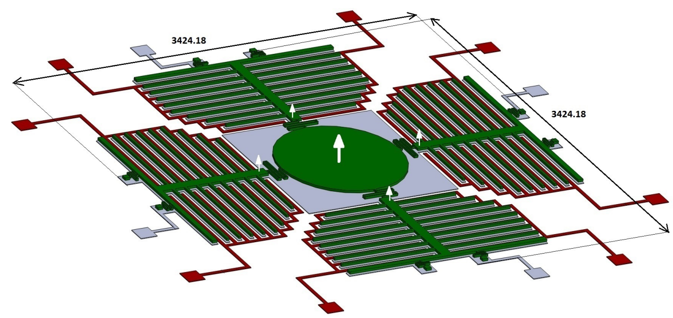

FIGURE 6: Low voltage actuator. Dimensions are in micrometers.

Due to symmetry, one eighth of the actuator is modeled in the finite element package ANSYS. The model includes moving fingers, aligned and unaligned fixed fingers and the anchoring spring. Boundary conditions of the actuator includes the symmetry boundary condition at the middle of the actuator, fixed nodes at the end of the anchoring spring, and restricted motion to the Z and Y directions at the end of the moving finger base, where it gets connected to the converting spring and the mirror plate.

Actuator Stiffness Before applying the voltages, the effective stiffness of the actuator is derived to compare with that of the previous actuator [15]. A constant pressure is applied on the bottom surface of the moving finger, and the displacement is found at the end of moving finger base. The constant pressure resembles the repulsive force generated by the electrostatic force on the moving fingers. Figure 7 is then obtained that shows the constant pressure multiplied by the actuator area (Force) versus the displacement of the end of moving finger base (mirror displacement). The effective stiffness for the low voltage actuator is the slope, 0.0067 N/m. The effective stiffness for actuator in reference [15] is driven here.

$$k = 4\frac{K_r}{L_e^2} = 4\frac{24.682\times10^{-9}Nm}{(997.43\times10^6)^2m^2} = 0.0992N/m \qquad (1)$$

where K_r is the rotational stiffness (the slope of torque versus rotation angle [15]), and L_e is the effective length (the slope of

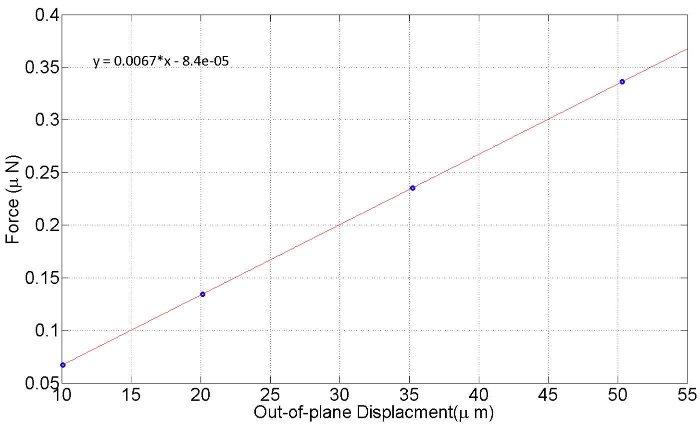

FIGURE 7: Force (constant distributed pressure multiplied by the moving finger area) versus mirror displacement. The slope is the effective linear stiffness.

out-of-plane displacement versus rotation angle [15]). So the low voltage actuator is 14.8 times softer than the previous actuator. Due to low stiffness, the acceleration such as gravitational acceleration may be a concern for this design that can be verified in future experiments.

Electromechanical Coupled Model The next step is to analyze the electromechanical model by applying voltages and obtaining the displacement of the low voltage actuator. To find the displacement of the moving finger in the z direction, static DC voltage from 0 to 25 Volts is applied to the unaligned fixed fingers and moving finger and the aligned fixed fingers are connected to the ground. The displacement of the moving finger in the z direction is illustrated in Figure 8 for voltages of 5, 10, 17.5, and 25 Volts, respectively. The displacement in the z direction increases along the length of moving finger base, which shows the rotation of the moving finger. The maximum displacement value was obtained at the end of the moving finger representing the out-of-plane displacement of the mirror. The moving finger maximum displacement is plotted against the applied DC voltage in Figure 9. It is inferred from the figure that to achieve 58 μm out-of-plane displacement, the low voltage actuator requires 25 Volts with almost a linear behavior for out-of-plane displacement versus the applied DC voltage.

The low voltage actuation is essential for user safety in applications such as cell phones, which require voltages less than 30 Volts. The redesigned low voltage actuator shows a larger out-of-plane displacement at a specified voltage compared to previous actuator [15]. Larger forces on the moving fingers of the redesigned actuator is created, but the stiffness is lower in the redesigned actuator. Lower stiffness can lead to lower resonant frequency and larger rise time. One application of the low voltage actuator is for auto-focusing using a mirror as proposed in [16]. Figure 10 shows a potential application of the mirror in auto-focusing of a cell phone camera. In reference [16], the required out-of-plane translation of the mirror was found to be 43 μm for focusing on an object located at 10 cm to 2 m. The smallest pixel size for the optical system was reported as 2.9 μm (corresponding to the pixel size of a 2 Mega Pixel camera). The low voltage actuator designed in this paper very well satisfies both of the requirements of the proposed auto-focusing module: the mirror translation, 58 μm vs. 43 μm; and low voltage, 25 Volts vs. 30 Volts.

CONCLUSIONS

In summary, a repulsive force actuator is introduced that moves a 1 mm mirror 58 μm out-of-plane at 25 Volts. The actuator is a redesigned version of a previous design [15] customized for low voltage applications. The actuator consists of four series of aligned, unaligned, and moving fingers anchored to the substrate through an anchoring spring and attached to a mirror plate through a converting spring. The aligned and moving fingers experience ground voltage and the unaligned fingers receives voltages. An asymmetric electrostatic field is then generated that creates a repulsive force on the moving finger and rotates the moving finger around the anchors. Once the four sets of fingers are attached to same potential difference, the moving fingers of each set rotate around their axes with the same angle of rotation, which creates a pure translation in the mirror plate attached.

The reduction in voltage is made through decreasing the width and spacing of the fingers, which led to a larger repulsive force on the moving finger in each unit cell of the actuator at small vertical gaps. Consequently the resulting torque and the angle of rotation were increased, thereby a larger pure translation of the mirror was created at a specified voltage. However, the redesigned actuator has a lower stiffness compared to the previous actuator [15], which can decrease the resonant frequency and increase the rise time. Future work includes testing and verifying the simulation results of the design prototype.

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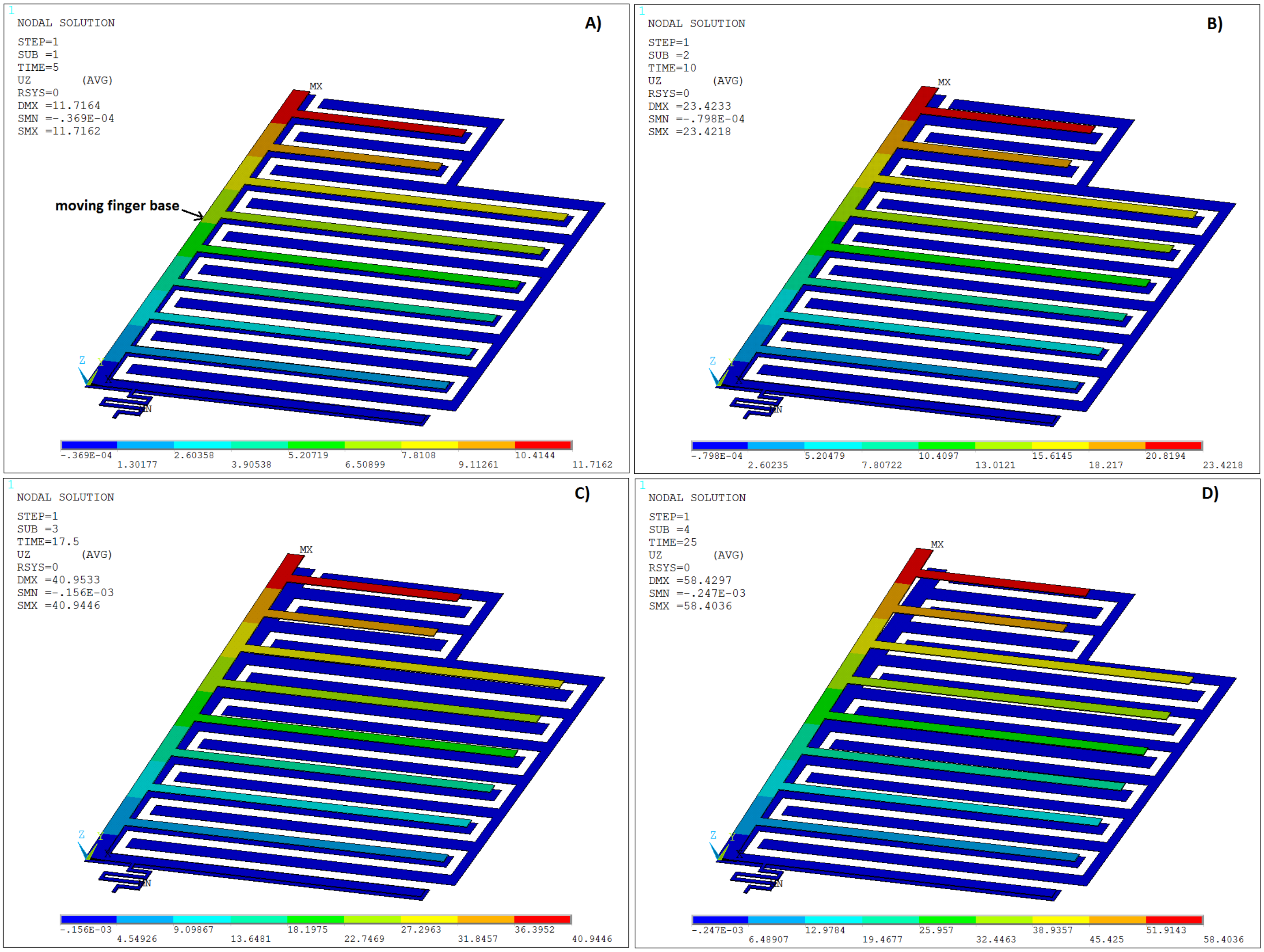

FIGURE 8: Displacement in the z direction when A)$V = 5\ Volts$, B)$V = 10\ Volts$, C)$V = 17.5\ Volts$, D)$V = 25\ Volts$

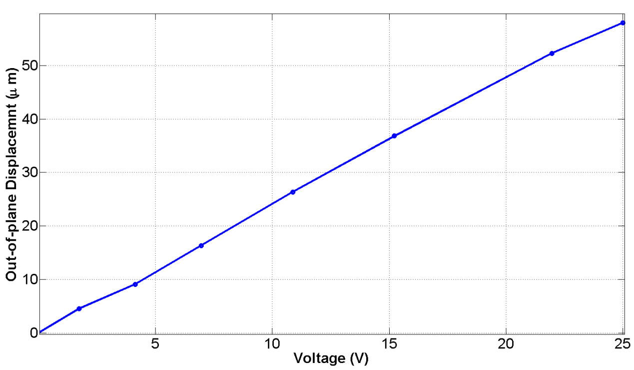

FIGURE 9: Out-of-dispalcements of the mirror versus voltage for the low voltage actuator.

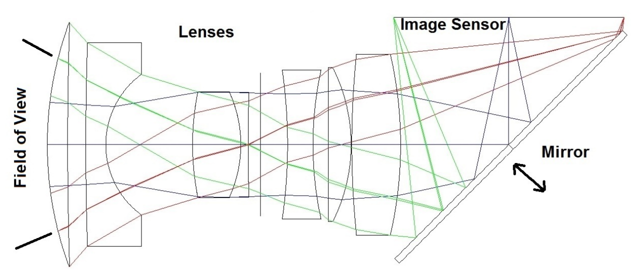

FIGURE 10: Illustration of application of the MEMS actuator to move the mirror in an auto-focusing module [16].

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