A High Stroke Actuator Micro-mirror Array Designed for Adaptive Optics

Quan Sun[1,2,3], Baozhu Yan[1,2,3] and Yi Yang[1,2,3]
[1]*College of Advanced Interdisciplinary Studies, National University of Defense Technology, Changsha, China*
[2]*State Key Laboratory of Pulsed Power Laser Technology, Changsha, China*
[3]*Hunan Provincial Key Laboratory of High Energy Laser Technology, Changsha, China*

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Abstract: A micro-mirror with large out-of-plane displacement actuator with three polysilicon layers fabrication process is designed for adaptive optics application. The optimized micro-mirror actuating structure consists of three individual levers, each of which is actuated by electrostatic attractive force with the plane-parallel structure to produce a large upward displacement at the end of the long arm of the lever with the lever principle. Finite element analysis (FEA) models are built to calculate the maximum upward displacement of the long arm. The actuator with 320 um long arm and 80 um short arm were designed by 2um thick Poly1 layer, while the electrodes were designed by Poly0 and mirror plate was designed by Poly2 with a polish process afterwards. The micro-mirrors can be tightly arranged in a hexagonal array to be applied in adaptive optics (AO) system as a deformable mirror. An AO simulation system is built to test the aberration correction effect of the micro-mirror array. The results showed that the 61 micro-mirror array is better than 37 micro-mirror array in aberration correction, which showed good application prospect of this high stoke micro-mirror array in AO systems.

1 INTRODUCTION

Recently, microelectromechanical systems (MEMS)-based micromirrors have received much attention. They have been applied in a wide range of areas, such as in optical switches (Chen W. C., et al., 2003) (Tsai C., et al., 2015) and displays (Yan J., et al., 2001) (Freeman M. O., 2003), high performance imaging including biomedical imaging (Zhang Y. H., et al., 2006) (Manzanera S. , et al., 2011) and astronomy imaging (Blain Celia, 2013) (Morzinski K. M. et al., 2006), and laser-based communication (L. MC A., et al., 2002) (Li J., et al., 2005) in adaptive optics. MEMS-based micromirrors have higher operating speed and lower mass than traditional technology fabricated deformable mirrors, and a potential for lower cost and integration with electronics through batch micro-fabrication processes. The latest developments in adaptive optics for compensating large amplitude, high order wavefront aberrations have pushed for high stroke, high spatial resolution deformable mirrors. Many recent papers have addressed design, modeling and fabrication of various types of micromirrors with large stroke (Dagel D. J., et al., 2006) (Sun Q., et al., 2010) (Lin P. Y., et al., 2011). The various micromirror prototypes are fabricated with different processes: commercial standard processes or custom-designed processes. Compared with custom-designed processes, commercial standard processes provide mature and stable runs, with a low cost and short fabrication cycle but with strict design rules which limit the performance of the fabricated device. One of the industry's longest-running standard processes is Multi-User MEMS Processes (MUMPs) (Carter J., et al., 2005). It provided a three layers fabrication process and has been widely chosen for micromirror prototypes fabrication (Zhang X. M., et al., 2001) (Sun Q., et al., 2009). The defect of this process is that it is difficult to make a smooth and flat mirror surface without polish after Ploy3 deposition. Most of the micromirrors reported to date employ electrostatic actuators because of their low power consumptions and fast response time (Zhang J. L., et al., 2003) (Chiou J. C., et al., 2007). In most applications, electrostatic actuators are preferred because of relatively simple in terms of design and fabrication; however, it suffers from the pull-in phenomenon, which limits its useful scan range. In this paper, we

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proposed a micromirror with large-stroke (about 8 um) electrostatic actuators designed by upgraded three layers polysilicon surface micromachining technology. The micromirror structure has a hexagonal mirror plate actuated by three levers and controlled by three electrodes, which exhibits a large stroke and tip/tilt/piston motion.

In this paper, we proposed an upgraded process with polish operation after the third polysilicon layer to design a large stroke micro-mirror. The paper is organized as follow. Section 2 describes the design details of micromirror structure with simulation results by finite element method (FEM) in COMSOL Multiphysics software which is provided software solutions for multiphysics modeling by the COMSOL Group. Section 3 reports two kind of micromirror arrays applied in adaptive optics simulation system to compare their compensation effect. And conclusions are presented in Section 4.

2 DESIGN OF MICROMIRROR

In the fabrication process, polysilicon is used as the structural material and phosphosilicate glass (PSG) is used as the sacrificial material. Twelve lithographic masks are used to pattern seven physical layers. The physical layers, from the substrate up, are as follows: 0.6μm of nitride (Nitride), 0.5μm of polysilicon (Poly0), 2.0μm of PSG (Oxide1), 2.0μm of polysilicon (Poly1), 0.75μm of PSG (Oxide2), 2.5μm of polysilicon (Poly2) and finally 0.5μm of gold (Metal), deposited on top of a thin adhesion layer of chromium. Poly1 and Poly2 are usually used to form the releasable structural layers, while Poly0 is fixed and generally used to form addressed electrodes and electrical interconnects. Nitride is used as electrical insulation between the polysilicon layer and the substrate. Metal layer is coated on top of Poly2 to serve as reflective surface. In order to reach a high fill rate of micro-mirror array reflect surface, we used Poly2 to design the mirror plate to a hexagon shape. As we know, there is residual stress after deposited polysilicon released, which will make the plate to bending deformation. One way to reducing the deformation is increasing the thickness of plate. While Poly1 is left to be made actuator, we design a 3um wide frame with Poly1 to connect the plate at its edge. In order to simulate the characters of our designed micromirror structure, a 3D solid model is built in COMSOL Multiphysics. The typical material parameters are acquired from COMSOL material library. Figure 1 shows the FEM simulation result of stress-induced deformation of mirror plate. The hexagonal side length of mirror plate model is 450um. The bowing value from the edge of plate to the centre is 0.517um.

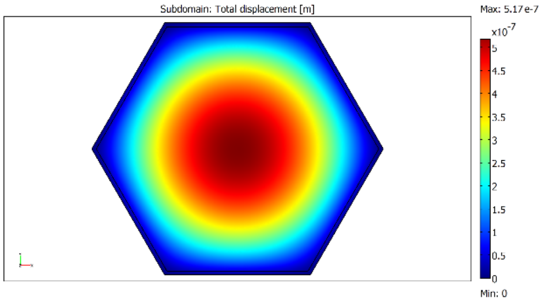


Figure 1: Simulation result of mirror plate deformation with FEM in COMSOL.

Figure 2 shows the bowing value versus mirror plate size. As shown, the bowing value increase with plate size. The AO applications need the mirror surface flatness no more than wavelength/5. So that we decide to make the mirror plate size to be 250um.

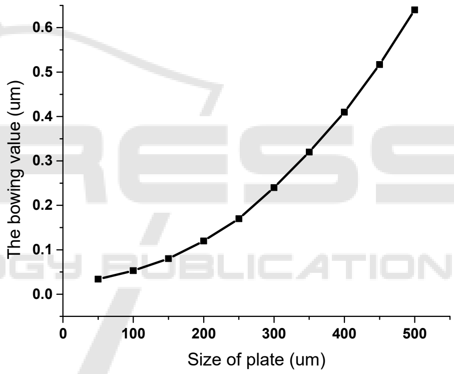
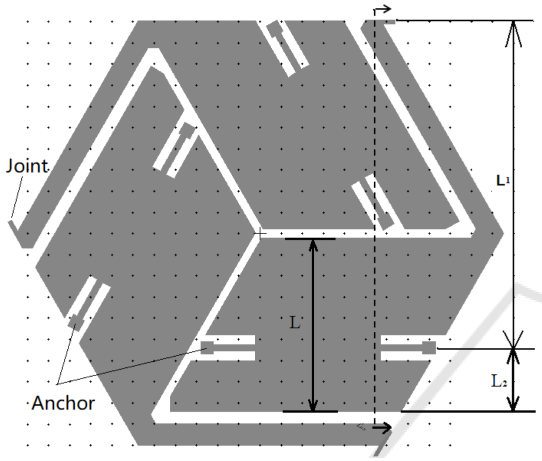
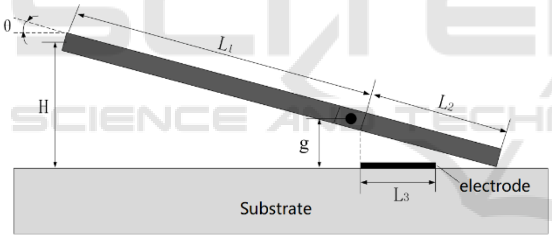


Figure 2: Simulation result of the bowing value versus mirror plate size.

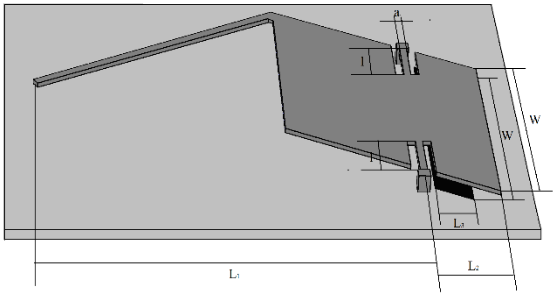
We chose Poly1 to make electrostatic actuators. In order to enlarge the upwards displacement of mirror plate, lever structure is decided to be used as actuator. The enlarge factor is equal to leverage ratio. And the lever actuator shape is also influenced by the mirror plate shape. As the mirror plate is hexagonal, and side length is 250um, three actuators need to be arranged symmetrically to achieve the mirror plate have three degrees of freedom motion. In order to obtain the longest lever length and the largest control electrode area, three lever actuators are designed to cross each other and have a special shape layout as shown in Figure 3(a) which could improve the effective utilization of Poly1 and reduce the print effect to above layer. Each lever has two anchor which connect the lever structure to the substrate and support cantilever to serve as rotation axis of the lever. The joint connects the Poly1 lever to Poly2 mirror plate. Figure 3(b) shows the section view of lever actuator. The lengths of two lever arms is represented by L1 and L2. While L represent the whole length of the lever, which equals 400um. H represents the lifting height, and g represents the gap between Poly2 and Poly1 after the sacrificial layer is etched. L3 represent the width of electrode fabricated by Poly0. Figure 3(c) shows the 3D model that we used to make simulation analysis by FEM.



(a) top view of three lever actuator layout



(b) section view of lever actuator



(c) 3D model of lever actuator

Figure 3: Lever actuators structure design detail.

Table 1 shows the FEM simulation results of pull-in voltage and maximum lifting height of levers with different structural parameters by Comsol. The conclusion showed that increasing resisting arm length would improve the max lifting height while would bring in high pull-in voltage. Higher voltage would cause more complicated control circuit and higher safety risk. On balance, we chose the parameters with L1=320um, L2=80um. And Figure 4 shows the simulation results of lifting height with the voltage applied on the electrode at the model parameters identified above. We can draw the conclusion that with this lever actuators, the micro-mirror could get a large out-of-plane piston displacement up to 8um.

Table 1: Simulation results of pull-in voltage and maximum lifting height of levers with different structural parameters.

Length of resisting arm L1 (um)	Length of power arm L2 (um)	Pull-in Voltage (V)	Lifting height (um)
335	65	420	10.30
330	70	357	9.42
325	75	299	8.66
320	80	246	8.00
315	85	204	7.41
310	90	169	6.88
305	95	141	6.42
300	100	119	6.00

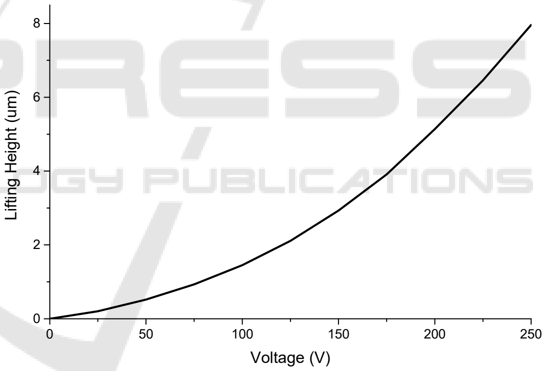
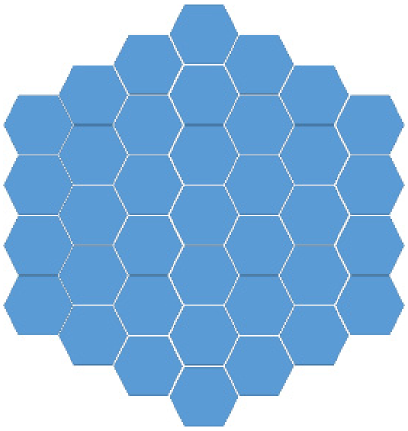


Figure 4: Simulation results of lifting height of lever with the voltage.

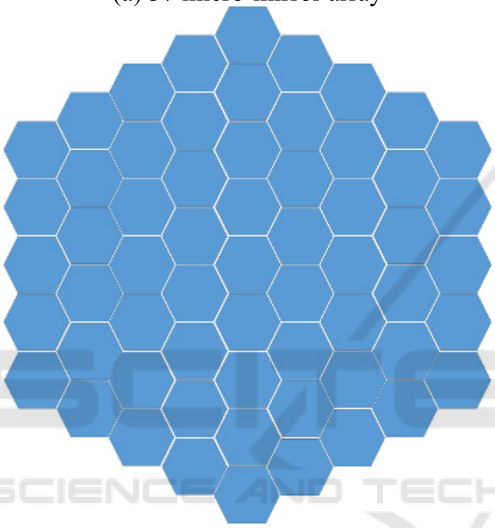
3 MICROMIRROR ARRAY APPLIED IN AO

Two size of micro-mirror arrays were built with our designed high stroke micro-mirror. As shown in Figure 5, one array consists of 37 micro-mirrors to form an about 1.75mm side length hexagon, while the other consists of 61micro-mirrors to form an about 2.2mm side length hexagon. These arrays would be use in adaptive optic (AO) system after fabrication.

We tested these arrays in an AO simulation system. The simulation system is built in SeeLight, a software tool for high fidelity modelling of advanced



(a) 37 micro-mirror array



(b) 61 micro-mirror array

Figure 5: Layouts of 37 micro-mirror array and 61 micro-mirror array.

optical systems such as laser active illumination and object detection systems which is developed by National University of Defense Technology and Institute of software, Chinese academy of Sciences. The principle of the software is based on wave optics theory with performing propagation by the angular spectrum theory and fast Fourier transform. As each micro-mirror in the array could make tip/tilt/piston motion. The max piston height is 8um. We used its characteristics to build a micro-mirror array model in the simulation system. Figure 6 shows the models schematic of AO simulation system. In the simulation system, the plane wave model outputs a plane wave beam, which transmits the aberration model and distorts its wavefront with the aberration in medium. The Hartmann Sensor model will measure the distorted wavefront, and calculates the control orders with the Centroid Algorithm model and the Control Operation model. The Micromirror Array Model receives the control voltage data from the Closed-loop Feedback model and operates every micromirror to the required height to correct the aberration wavefront of the input beam.

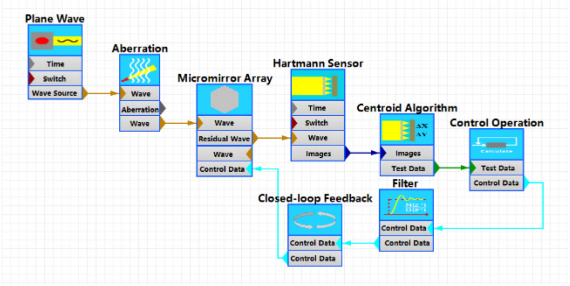


Figure 6: The simulation model schematic of AO system built in SeeLight software.

Figure 7 shows the aberration wavefront map generated in simulation system which PV aberration is about 6um. The size of map is transformed to be equal to the two sizes of micromirror array, separately. And Figure 8(a) shows the piston motion heights of 37 micromirror array, while Figure 8(b) shows that of 61 micromirror array. The RMS of corrected residuals were 293nm and 123nm respectively. Apparently, the micro-mirror number of the array is larger, the AO aberration correction is better. But larger number of micro-mirror would bring out more complex control circuit and closed-loop algorithm.

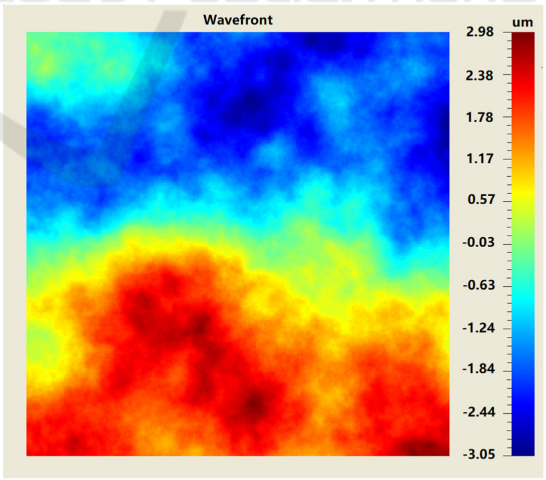
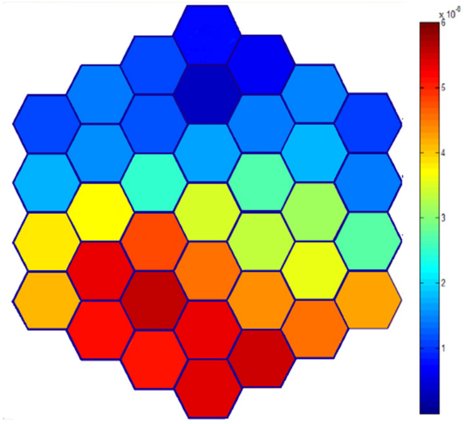
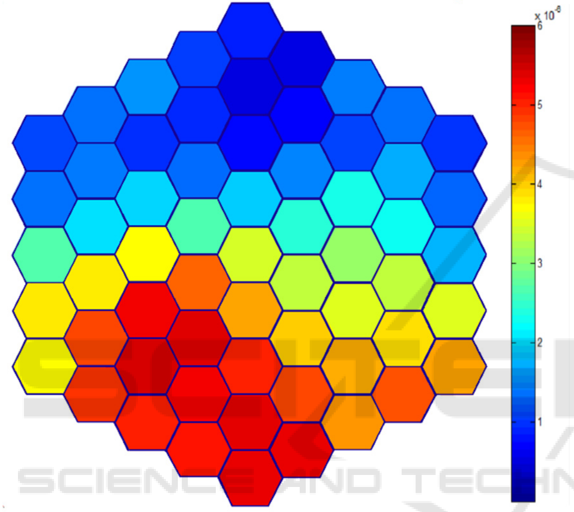


Figure 7: The aberration wavefront map for AO to measure and correct.



(a) 37 micro-mirror piston motion heights



(b) 61 micro-mirror piston motion heights

Figure 8: The aberration wavefront map for AO to measure and correct.

4 CONCLUSIONS

In this paper, a micro-mirror with large out-of-plane displacement actuator is designed for adaptive optics application. The micro-mirror with three lever actuators is designed by optimized three layers fabrication process. Micro-mirror structure models were built in Finite element analysis (FEA) software Consol to get the optimum structural parameters. The micro-mirrors were tightly arranged in a hexagonal array to serve as a deformable mirror. An AO simulation system was built to test the aberration correction effect of the micro-mirror array. The results showed that the 61 micro-mirror array was better than 37 micro-mirror array in aberration correction, which showed good application prospect of this high stoke micro-mirror array in AO systems.

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