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A low voltage and large stroke Lorentz force continuous deformable polymer mirror for wavefront control

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ABSTRACT

This paper presents a low voltage, and large stroke Lorentz-force actuated continuous deformable polymer mirror for adaptive optics. A 5 × 5 actuator array clamped on the rigid mounting rail are formed from single crystal silicon flexible serpentine springs on either side of a rigid crossbar containing a narrow contact pillar. For the mirror, an epoxy-based SU-8 photoresist is used, which enables low voltage operation combined with Lorentz actuator. The Lorentz DM were tested and demonstrated a large 40 μm deformation at 9 mA actuation current, and needing <1 V operation. This Lorentz DM would operate 2 kHz frequency with 40 μm stroke, which can be suitable for large deformation adaptive optics application.

1. Introduction

The miniaturization of adaptive optics (AO) systems has attracted much attention over the past several decades. AO systems can compensate for image wavefront aberrations and are being explored for various applications, such as Earth-based telescopes [1–3], microscopy [4–6], retinal imaging [7–10], optical communication [11], and high energy lasers [12]. The required stroke depends on the application, with some requiring 10's of μm motion. For example [5], describes an AO system for high NA confocal microscopy of human skin. It requires a large focal range and 30 μm stroke.

AO systems employ actuators to deform the mirror surface to actively correct the distorted image wavefront. MEMS fabrication has enabled the miniaturization of deformable mirrors (DM), reducing power consumption and significant space occupancy. They have enabled batch fabrication of numerous actuator elements together.

An early version of a MEMS-based DM was fabricated by Boston Micromachines Inc. in [3]. A rigid polysilicon membrane was used with an electrostatic transducing mechanism. The maximum mirror stroke was 1.9 μm, requiring a high voltage of 241 V. Later on, Fernandez et al. [20] replaced the polysilicon membrane with a softer gold membrane. The gold mirror was able to move 6.4 μm with 360 V actuation voltage. In order to lower the driving voltage further, a flexible organic polymer was employed. An epoxy-based SU-8 membrane combined with an electrostatic actuator was reported in [15]. It achieved a stroke of 12 μm at 220 V. In [19], a polyimide DM showed a 39 μm stroke at 195 V. In [18], a piezoelectric unimorph microactuator was used to deform a 100 μm thick single crystalline silicon mirror. A 7.4 μm stroke was achieved at 100 V, and the mirror had a resonance frequency of 18 kHz.

One of the major research challenges in AO technology is the ability to achieve sufficient mirror deformation stroke with low voltage operation. In the case of conventional MEMS electrostatic and piezoelectric actuated DM, large stroke often requires actuation voltages over 100 V. Such high operational voltage causes many problems in integrating the MEMS DM with on-chip driving circuits. Therefore, in these cases, the high voltage MEMS DM requires multiple wire connections to external high voltage amplifiers, which results in a large space occupancy, high power consumption, and increased complexity of the system.

A low voltage large stroke DM was demonstrated in [17]. It employed an electromagnetic actuator and polymer mirror. The mirror consists of a thin polyimide membrane (2–5 μm thickness) covered with a permanent magnet matrix, and was mounted above an array of planar microcoils on a 50 mm diameter substrate. This work offered a large 15 μm stroke at below 1 V with 2.5 A current. However, this electromagnetic coil based DM required high power, which can result in significant local heating and optical distortion

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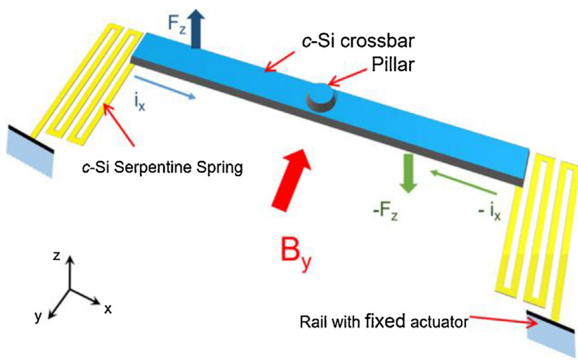

Fig. 1. The design of Lorentz actuator and working principle.

due to thermal convection of surrounding air. Additionally, this particular device suffered from uneven stress points on the mirror at the glue points of the magnets, causing optical aberrations.

Lorentz based magnetic actuators offer many advantages over the above efforts. They offer simple actuator design, and low voltage operation with no magnetic hysteresis. Bi-directional motion ability offers out-of-plane push and pulling motion. This allows the correction of surface flatness issues, such as due to gravity-induced deformation on mirror membranes. These advantages, along with fast response and reasonable power consumption, make them ideal for large stroke applications.

A Lorentz actuator design with large stroke and thermal stability was presented in [13]. The actuator showed a deflection of ± 150 μm motion at ± 15 mA current, in a 0.48 T magnetic field. The magnetic field was enabled by a small permanent magnet located below the actuator.

In this paper, we describe the implementation of the actuator design of [13] to deform a mirror surface. Flexible SU-8 is employed as the base structural material of the mirror since it provides lower Young's modulus relative to silicon-based membranes [14]. SU-8 is well known as a chemically stable and mechanically robust material. It is a negative photoresist which is compatible with lithographic and the other semiconductor fabrication process. The SU-8 is coated with aluminum metal to form the reflective mirror. The Lorentz actuator array of [13] is located below the continuous deformable polymer mirror element.

2. Design

The demonstrated Lorentz actuator design and the working principle is shown in Fig. 1. The actuator is designed based on flexible supporting serpentine springs on either side of a central thick and rigid crossbar above a permanent magnet. The rigid crossbar is intended to prevent the crossbar from bending due to the opposing force when the actuator deforms the mirror. Both the crossbar and serpentine springs are made of single crystal silicon, etched from a crystalline silicon wafer. The serpentine springs provide mechanical support for the crossbar, a pathway for electrical current, and heat sinking to the substrate. To allow for the current flow necessary for the Lorentz force mechanism, the crossbar and springs are coated with 1.5 μm thick aluminum.

Fig. 2a shows a fabricated 5 × 5 actuator array. The crossbars are rotated 45 degrees to obtain maximum Lorentz force by enlarging crossbar length. The 2080 μm (length) × 200 μm (width) crossbar contains a central pillar which is used to contact the above mirror to be manipulated in Fig. 2c. The height of this pillar prevents the crossbar from touching the mirror. Each actuator is connected to a rigid anchor rail, also etched from the silicon wafer. The narrow but rigid (300 μm thickness) anchor rails allow for a large array of actuators to be fabricated in close proximity to each other. Moreover, the rails dissipate heat and provide space for an electrical wire connected to an external circuit. Fig. 2b shows the Lorentz DM system after combining the mirror phase sheet (above) and actuator substrate (below).

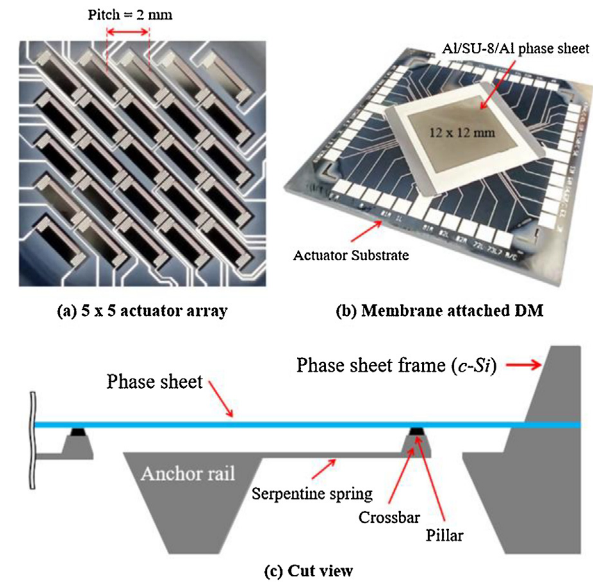

Fig. 2. (a) Microscope image of a fabricated 5 × 5 Lorentz actuator array. (b) Membrane attached deformable mirror (DM). (c) Side view.

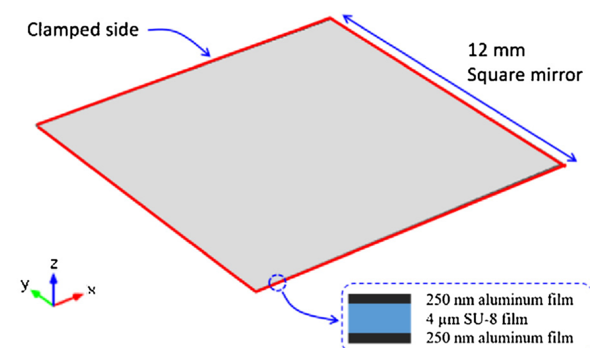

Fig. 3. Boundary conditions of the mirror and its vertical structure (lower right corner).

Table 1
Material properties for the mirror.

Properties / Material	SU-8	Aluminum
Density (kg/m^3)	1219	2700
Young's Modulus (GPa)	2	70
Poisson's Ratio	0.22	0.35

In order to estimate the dynamic performance of the developed Lorentz DM, the resonant frequency of the device is simulated using COMSOL Multiphysics software under the boundary conditions shown in Fig. 3. The model consists of a 12 mm × 12 mm Al/SU-8/Al membrane mirror. All sides of the mirror structure (red line) are clamped. Here, the clamping means that there is no translation or rotation permitted ($x = 0$, $y = 0$, and $z = 0$). The mirror is constructed by coating a 250 nm thick aluminum on both sides of the 4 μm thick SU-8 film. The material properties used in this model are listed in Table 1.

Fig. 4 shows the first two resonance modes and corresponding frequency. The mirror has a simulated response of 231.96 kHz. The mass and spring constant defines the resonant frequency of the DM