Feasibility study of a MEMS-Based High-Density, Segmented, Phase Manipulating Optic

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Abstract

Current state of the art optical systems often employ corrective devices in order to manipulate the wavefront of a throughput signal. Such devices are often expensive, require high voltages and are limited in their ability to correct errors with high spatial frequencies. MEMS processes, however, are effectively limitless in their capability to achieve high actuator densities therefore capable of correcting high spatial frequency error. The proposed device is an affordable MEMS alternative to traditional systems. The device is capable of static wavefront error correction for spatial frequencies up to 0.2mm with a resolution on the order of 10 nanometers. The full range of 2 micron actuation can be addressed with less than 20 Volts of actuation potential.

Introduction

Many optical imaging/focusing systems employ the use of state of the art equipment and techniques to maximize the quality of the image achievable. Such systems include, but are not limited to astronomical telescopes, satellites, targeting systems and other military applications. The extremes of sophistication include accurate optical fabrication, precision alignment and in some cases, dynamically correctable optics to fine-tune the final system. Such correctable optics, otherwise known as deformable optics, geometrically deform optical surfaces in order to modify the wavefront of the incident signal.

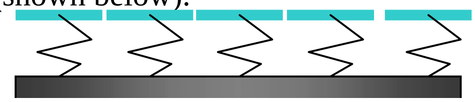
The driving force for wavefront correction is to limit diffraction effects in the image. Diffraction effects essentially describe the departure from pure geometric ray physics of a propagating electromagnetic wave. In short, it describes the natural blurring of the "perfectly" focused image. By limiting the wavefront error of the focused beam the amount of blurring can be controlled. The Strehl number is a number that can be used to represent image quality. It can be thought of as the ratio of the actual image quality (actually far field intensity) relative to that of the theoretically possible, a.k.a. a diffraction limited system. The effect of wavefront error on the Strehl can be mathematically expressed as:

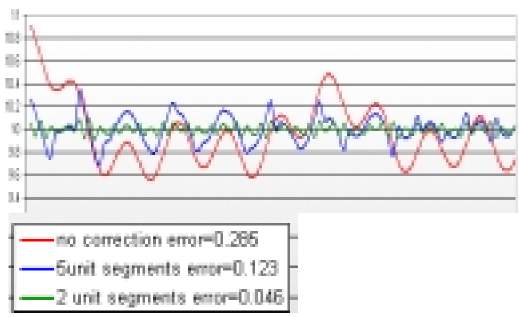
$$S \propto e^{-\Delta\phi^2}$$

where ϕ^2 is the variance of the wavefront. This quantitatively demonstrates the reason for minimizing wavefront error.

State of the art deformable optics are currently fabricated using a continuous face sheet (optical surface) actuated via piezo-electric stacks. Such deformable mirrors often have on the order of 100 actuators that manipulate the face sheet. The reason for the relatively low number of actuators is two fold. Said deformable mirrors are typically assembled by hand. That is, the actuators are manually bonded to the substrate and face sheet. This labor-intensive task limits the number and scalability of actuator density due to cost restrictions. Furthermore, the limited actuator density inhibits the system from correcting wavefront error at high spatial frequencies. Secondly, in some applications these systems are used for dynamic applications (up to 100's of Hz). Due to the relatively high demand on the control system, the number of actuators is limited in order to keep the control processing loads reasonable.

The proposed device would allow for an inexpensive high actuator density device for use in removal of static (or low temporal frequency) wavefront error from complicated optical systems. The basic concept of the device is to utilize a large array of micro mirrors capable of pure piston actuation to locally correct the wavefront error (WFE) of an incident beam (shown below).





The error (standard deviation) can be shown to decrease with decreasing actuator size. This local correction results in the reduction of the variance of the WFE and hence an increase in Strehl. The efficiency of such a system increases with increasing actuator density making a MEMs system favorable.

Device Requirements

In order for such a device to be competitive in the limited market of deformable optics it must either have higher performance than current technology and/or comparable performance for lower cost. If the cost per device can be made appreciably smaller, it is possible for adaptation into new markets. Based on these assumptions, the following design requirements were established for this device study:

1. Useable actuator throw of 2 µm with stability to 1% (.02 µm)
   This is due to the fact that a large number of optical systems deal with wavelengths from near IR (~2 µm) through visible (down to 0.4 µm)
2. Driving voltage <100 Volts
   Comparable to current technology
3. Comparable cost to current systems

Device Characteristics

The proposed MEMS based micromirror structures are made of four polycrystalline silicon springs and a highly reflective, flat mirror surface. These mirrors are electrostatically actuated with a voltage potential that is applied between the charged mirror surface and the electronic layer whose charge can be altered. As a greater potential is applied, the top plate moves towards the lower plate, which is fixed to the substrate. As the upper plate moves, the mirror is spring guided in a vertical motion, allowing variable positioning, which is used to cause variation in the phase of the incident beam.

Our design allows for 100x100µm mirrors placed in a 500x500 array with 1µm spacing that spans a 4 in.^{2} on a 4 in. wafer. The reflective surface of the array occupies 98% of the total device thereby minimizing the optical loss. The operating voltage varies from 0-16.4V, which provides for the 2µm throw with nanometer accuracy.

Device Fabrication

The fabrication of the phase correcting mirror arrays begins with a silicon substrate on which an electrical isolation layer of nitride is deposited. The next layer contains the electrical circuitry of the system that provides the variable electrical biases necessary to actuate the mirror surfaces.

This layer is electrically sealed with another layer of nitride.

The fabrication of the spring supported mirror surface begins with a patterned layer of polysilicon that will eventually serve to maintain the mirror's electrical bias. The mirror supporting springs are constructed on this layer of polysilicon using polysilicon and polysilicon glass (PSG), which is used as the sacrificial layer. Through a series of polysilicon and PSG depositions and planarization steps, the springs are constructed. The springs are 0.5μm thick with 2μm thick pads that connect it to the substrate and mirror. Finally, a layer of polysilicon is deposited on top of the PSG encased springs and planarized. The individual mirror systems are then separated by a timed 1μm line width etch. This separation etch also creates the etch pits that allows for the HF release etch of the PSG. In order to eliminate diffusion problems, the solution is vigorously stirred. Although the amount of PSG to be etched is significant, the HF selectivity of polysilicon to PSG is theoretically infinity. Furthermore, the HF selectivity of nitride to PSG is around 1600. Therefore, complete release can be guaranteed by over etching without the concern of damage to the structures. Lastly, a layer of gold is deposited to create the electrostatic actuated mirror surface. In total, the process requires four planarization steps, six masks, seven etches, and twelve depositions.

Modeling and Analysis

The following is the mathematical derivation of the predicted performance characteristics of the device. This includes the electrostatic force generated as a function of the applied voltage differential as well as the compliance of the springs. Together, this information can be used to predict the required voltage to produce a given mirror displacement.

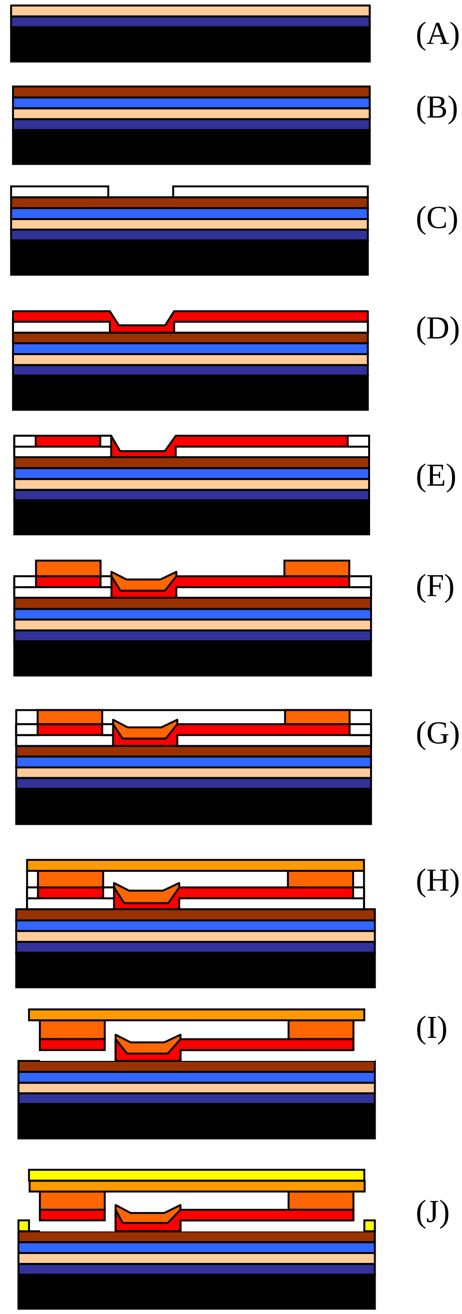


Figure 1: (A) Silicon wafer with nitride coating (2μm) and electronics layer. (B) Nitride layer 2 (2μm) and polysilicon 1 (1μm). (C) PSG 1 (2μm). (D) Polysilicon 2 (0.5μm). (E) PSG 2 (0.5μm). (F) Polysilicon 3 (1.5μm). (G) PSG 3 (1.5μm). (H) Polysilicon 4 (2μm) and separation etch. (I) Release Etch. (J) Gold 1 (0.1μm).

Mechanical properties of the springs (modeled as guided cantilever beams):

The spring constant, k, of a rectangular guided cantilever is given by

$$k = \frac{Ewt^3}{l^3}$$

where w, l, and t are the width, length and thickness of the beam, and E is the elasticity of the material. The Young's modulus of elasticity for silicon in a <100> crystallographic direction is 166 Gpa.

For our dimensions:

w = 2 μm

l = 82 μm

t = 0.5 μm

E = 166 Gpa

$$k = 0.075 N/m$$

Accounting for all four beams,

$$k_{total} = 0.3 N/m$$

Electrostatic actuator properties and requirements:

In order to achieve a desired gap closing actuator throw of 2 μm, we need to provide an appropriate capacitance gap using the following relationship:

$$g_{pull-in} = \frac{2}{3} g_0$$

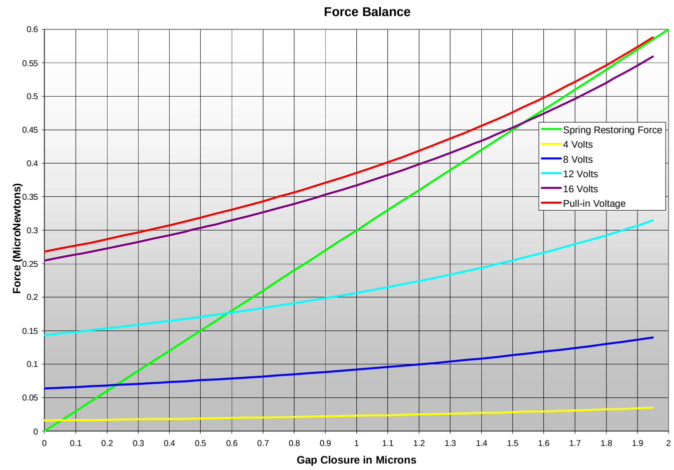
$$g_o = 6 \mu m$$

The remaining 2/3 of the actuator are not useable due to the inherent instability in the system. This instability region is avoided by a mechanical stop that prevents actuation into this regime.

The voltage controlled electrostatic gap closing actuator force can be obtained with the following equation

$$Force = \frac{-\partial w^*(V,g)}{\partial g} = \frac{\varepsilon A V^2}{2g^2}$$

With this expression, along with the spring stiffness, the performance of the device can be numerically calculated. Shown below is a numerical plot to study the force balance on the system for five different voltages.



Using these numerical values, a plot of voltage vs. displacement can be constructed (shown below)

The pull-in voltage, which can be analytically calculated, is 16.4 Volts. The resolution of the device can be calculated using the sensitivity of gap closure to voltage change, along with the stability of the voltage itself. As shown in the plot above, the voltage-gap sensitivity increases with gap closure tending to infinity as the gap approaches the pull-in value. Using a conservative value for voltage stability of +/-0.05 V, the accuracy of the device can be calculated to range from 0.75 to 12.5 nanometers for respective gaps of 0 to 1.5 microns.

A dynamical analysis of the device was deemed unnecessary due to the static nature of the device. That is, any amount of dynamic wave front error correction would be unfeasible due the large number of degrees of freedom in the feedback loop.

Market Analysis

One of the primary advantages of the device, aside from its resolution improvements, is its relative cost compared to current technology. At the present time, corrective optical devices feature single 3 to 6 inch diameter mirrors with actuator arrays on the order of 10 X 10. These actuators, which are used to tilt or raise the mirrors to adjust the signal, typically cost about $1000 each, and result in a total mirror cost in excess of $100,000. On the other hand, the device described in this paper would utilize a MUMPS-like process, costing roughly $10,000 per 4-inch wafer. Additional processing needed for the deposition of electronics and for gold sputtering would double the cost to about $20,000 per wafer. After factoring in other possible costs, as well as a 100% markup in price, each wafer will be available for approximately $50,000. The 4-inch wafers would feature an array of 500 X 500 individually actuated mirrors, or 25,000 mirrors. Because the fabrication of the device is a batch process, the device could be sold on a per-wafer basis rather than a per-actuator basis, dramatically decreasing the cost while increasing resolution.

While the market is not particularly large for such a product, it would definitely benefit from a higher quality product at a lower price. Currently there are roughly 45 large optical telescopes in the world, with about 10 more under construction. If effective, this corrective optics device could be sold to the many telescope manufacturers and operators, and also has potential applications in medical imaging, satellite systems, as well as military uses such as targeting systems.

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