Prototype MEMS piston mirror array for pulse shaping in UV

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A MEMS device consisting of an array of movable mirrors to be used in ultrafast pulse shaping was fabricated. The device operates by changing the free space path length of individual spectral components of the optical pulse. We aim to extend the operation range to lower wavelengths than current liquid-crystal devices. 400 nm piston motion was demonstrated at around the desired operation voltage of 10 V. The flatness of the mirror and optical loss are both acceptable. More measurements are necessary to characterize the dynamic response, uniformity in the array, and cross-talk between adjacent elements.

I. INTRODUCTION

Ultrafast optical pulses are used in a wide variety of applications in the fields of physics, chemistry and in industries such as telecommunications. Pulse shaping refers to the process of altering the amplitude and/or phase profile of an incident optical pulse to produce a new optical pulse. The ability to generate tunable, arbitrary waveforms is important in many fields, such as controlling certain chemical reactions and compensating for pulse deformation in dispersive media such as optical fibers [1, 2].

The general method of pulse shaping is illustrated in Fig. 1. First, a pulse is projected onto a grating, which breaks it up into its spectral components. Individual spectral components are then focused by the lens onto separate locations on the spatial light modulator (SLM). The SLM imparts a specific phase and/or attenuation to each spectral component. The spectral components are then directed by a second lens onto another grating. Here, the spectral components are recombined, resulting in an outgoing pulse with modified amplitude and phase profile compared to the incident pulse [3].

Considerable efforts were devoted over the past two decades to improving the performance of SLMs. Early methods employed masks created by lithographic techniques. Even though this scheme of pulse shaping is very reliable, the masks could not be modified in real time, and a new device had to be fabricated for every waveform. Dynamic devices that could easily be manipulated and produced reliable results are highly desirable. A number of different approaches were employed to produce programmable SLMs that can readily be manipulated by computer control [2, 3]. Among these, liquid-crystal (LC) arrays are the most widely used and have proven to be the most reliable for shaping pulses as short as 13 fs. The operation of LC devices depends on changes in the refractive index of the liquid crystal in the presence of an electric field. LC devices for pulse shaping consist of a thin layer of liquid crystal placed between two pieces of glass. The inside surface of each piece of glass is coated with a transparent conductive material. This conductive material on one of the glass pieces is broken up into individual electrodes controlled separately by a computer. By applying different

![Fig 1. Illustration of the apparatus for femtosecond pulse shaping. Figure taken from reference [3].](image-url)
voltages to individual elements, the refractive index of each channel can be independently controlled. This change in refractive index in turn leads to different phase shifts of the separate spectral components [3]. The downside of LC devices is that the transmission drops significantly at short wavelengths, cutting off at 440 nm. This limits the effectiveness of LC devices in shaping fast optical pulses in the ultra-violet.

In this project we explore an alternative way to introduce controllable phase shifts to the spectral components. Our aim is to extend the operation of the SLM to shorter wavelengths while not sacrificing the optical performance and programmability of the device. Using silicon micromachining, we fabricate a prototype device that could impart programmable phase shifts to the spectral components for wavelengths down to 200 nm. This device consists of an array of movable mirrors. Each mirror is independently capable of motion perpendicular to the substrate when electrostatically actuated. The phase shift of separate spectral components is controlled by altering the free space path length (see Fig. 2 for illustration) in contrast to LC devices where the phase shift is produced by changing the refractive index. For optimal functionality, it is desirable to have quick response time, high fill factor, a 400 nm piston motion, low cross-talk between adjacent mirrors, uniformity in the response of the mirrors, and a fairly flat surface. All these issues will be addresses later in the paper.

II. MEMS

The array of movable mirrors to be used for phase modulation is a microelectromechanical device. Microelectromechanical systems (MEMS) are movable devices constructed using semiconductor fabrication technology. Our devices consist of layers of polysilicon separated by silicon oxide on a silicon wafer. After each layer of polysilicon or oxide is laid down, it is coated with a layer of photoresist, which is selectively exposed through a photomask to certain wavelengths of light. The exposed parts of the photoresist go through a chemical change. Depending on the type of photoresist, either the exposed or the unexposed parts are washed away, leaving a layer of patterned photoresist covering the underlying layer of polysilicon or oxide. This photoresist layer acts as a protective mask for the subsequent etching of the underlying layer, allowing only the exposed parts to be etched away. After the etching step is completed, the photoresist is washed away, and we are left with a polysilicon or oxide pattern. This process is repeated to build up a stack of alternating layers of polysilicon and oxide. Physical and electrical contact between two polysilicon layers can be created by etching away part of the oxide layer between them. At the final step of the fabrication, the oxide is removed with hydrofluoric acid (HF) and we get a released structure that is capable of motion. Fig. 3 illustrates a cross sectional view of a MEMS device before and after releasing. Details of the design will be discussed in the next section.

Fig. 2. Illustration of phase shifting as the free space path length is changed. Show mirrors moving. Figure taken from reference [8].

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Fig. 3. Cross sectional view of a MEMS device before (above) and after (below) HF etching.
III. MIRROR DESIGN

The prototype micromachined mirror array consists of 6 identical 3.5 µm thick and (90x90) µm² plates free to move perpendicular to the substrate. The plates are secured to the substrate by four serpentine springs along two opposing sides of the mirrors. Fig. 4 is an image of the mirrors taken by a scanning electron microscope (SEM). To create a displacement, we apply a driving voltage between the top plate and an electrode that is fixed under the plates. The driving voltage produces electrostatic attraction between the top plate and the electrode. At equilibrium the electrostatic force is balanced by the restoring force of the springs. The springs were designed to allow a 400 nm displacement at around 10 V. 400 nm of motion is necessary to impart phase shift of 2\pi to the long wavelength component of the spectrum of the pulse. An actuation voltage of 10 V is chosen so that the existing electronics for LC devices can be used.

For the mirrors to be able to move 400 nm at 10 V, the restoring force supplied by the spring must balance the electrostatic force. From Hook’s law, the restoring force of the spring is

\[ F_k = kz, \tag{1} \]

where \( k \) is the spring constant, and \( z \) is the displacement along the z-axis. The electrostatic force between two parallel plates is given by

\[ F_E = \frac{\varepsilon_0 AV^2}{2(d-z)^2}, \tag{2} \]

where \( A \) is the area, \( V \) is the applied voltage, \( d \) is the initial separation (at 0 V), and \( z \) is the displacement. By setting these two equations equal to each other at 10 V, an initial separation of 2 µm, and a displacement of 400 nm, the spring constant in the z direction is calculated to be 3.5 Nm⁻¹. The spring must also be stiff along the x and y axis to avoid unwanted motion in those directions. We have decided to use a serpentine spring with the dimensions given in Fig. 5. The length of the springs is perpendicular to the side of the mirror where they are attached.

The z-axis component of the spring constant for this spring is given by

\[ K_z^{-1} = K_{z1}^{-1} + K_{z2}^{-1}, \tag{3} \]

where

\[ K_{z1} = E \left( \frac{t}{l} \right)^3 \frac{w}{N}, K_{z2} = \frac{12\tau}{N^2s^2}, \]

and

\[ \tau = \frac{E}{2(1+v)} \frac{w^3t}{3Nl} \left[ 1 - 0.63 \frac{w}{t} \left( 1 - \frac{1}{12} \left( \frac{w}{t} \right)^4 \right) \right]. \]

Here, \( t \) is the thickness of the material, \( l \) is the useful length of each turn, \( w \) is the width of the spring, \( s \) is the pitch, \( N \) is the number of turns. \( E \) is the Young’s modulus, \( v \) is Poisson’s ratio, and \( \tau \) is the torsional stiffness as given in the equation above.

In our first design, the following parameters were chosen for the spring: 5 turns, 59 µm for the length (this takes into account that the two outer beams are longer), 2 µm for the thickness, and 5 µm for the pitch. Using an SEM, we found
that the actual width of the springs in the fabricated device is 1.6 µm instead of 2 µm due to linewidth losses in the fabrication process. The Young’s modulus and Poisson’s ratio for polysilicon are approximately 120 GPa and 0.30 respectively. The exact values of these two parameters in our devices may vary depending on the fabrication conditions. Using the above parameters, equation (3) yields a spring constant of 4.42 Nm⁻¹. Referring back to Eq. (1) and (2), the voltage required to produce a 400 nm motion is 11.23 V. This voltage is still achievable with existing electronics used to drive LC devices.

The maximum attainable displacement is also limited by the initial distance between the mirror and the electrode. Setting Eq. (1) and (2) equal to each other yields the following equation
\[ k z = \frac{\varepsilon_0 A V^2}{2(d - z)^2}. \] (4)

Notice that Eq. (4) is a cubic equation in z. V is plotted as a function of z in Fig. 6. Below 12.1 V, there are 3 equilibrium positions corresponding to each voltage. The first segment is a stable equilibrium when the electrostatic force balances and the restoring force of the spring. The second segment represents an unstable equilibrium. The third segment corresponds to the state of the mirror after it has snapped down and is in physical contact with the electrode. From Fig. 6, the maximum attainable displacement without the top plate coming into contact with the electrode is 1/3 of the initial gap. Any increase in voltage after this point will cause the mirrors to snap down. This ratio is universal for the parallel plate geometry and is independent of any of the constants used. In our case, an initial gap of 2 µm yields a maximum displacement of 0.66 µm. To produce the appropriate phase shifts, a maximum of 400 nm displacement is required, which is well within this limit.

The resonance frequency of the device is given by
\[ f = \sqrt{\frac{k}{M}}, \] (5)

where k is the spring constant and M is the mass of the mirror. Using the density of polysilicon (2.33 g/cm³), the area (90x90 µm²), and the thickness (3.5 µm) of the mirror, the mass of the mirror is 6.61x10⁻⁸ gm. This gives a resonance frequency of 25.9 kHz with spring constant of 4.42 Nm⁻¹.

IV. DATA

A WYKO optical surface profiler was used to measure the actuation of the mirrors as a function of voltage applied to bottom electrode. Measurements were taken at small intervals between 0 and 13 V as illustrated in Fig. 7. Using Eq. (4) and the calculated spring constant, displacement is plotted as a function of V in the dashed curve. This curve overestimates the voltage needed. Reducing the spring constant to 3.9 Nm⁻¹ gives a closer fit, indicating snap down above 11.4 V. The reason for the difference

Fig. 6. The graph represents voltage as a function of displacement. The graph uses the parameters discussed earlier in the paper.

Fig. 7. The graph represents displacement as a function of voltage for the data taken by a surface profiler. The red line is a fit using Eq. (6) and the calculated spring constant. The blue fit uses the same equation at a lower spring constant.
between the calculated and the measured spring constants might be attributed to variations in the Young’s modulus, and Poison’s ratio of the polysilicon. Based on the measurements, the voltage needed to produce a 400 nm displacement is 10.6 V. This is closer to the desired 10 V than the designed value.

The cross-talk between adjacent mirrors was an initial concern. When voltage is applied between a mirror and the underlying electrode, charge may build up that can influence the position of the adjacent mirrors. If this effect is too large, it will affect the performance of the mirror array. Fig. 8 is a plot of the displacement of three mirrors as voltage is applied to the central mirror. Based on measurements taken by a surface profiler, there was no measurable cross-talk within the noise levels of the measurements. More precise measurements will be needed to obtain more conclusive results.

The pulse shaping scheme in Fig. 2 assumes that the MEMS mirrors are perfectly flat. During the design process it was anticipated that built-in stress gradients in the polysilicon might cause curving of the mirrors. If the curvature were significant the reflected spectral components of the pulse would diverge. This could be corrected by subsequent optical elements if the curvature across the array of mirrors was constant. Compensation will be very difficult if the curvature of the mirror varies for different elements of the array. From optical profiler measurements of the mirrors no measurable curvature was found. Fig. 9 shows a cross section of one of the mirrors. Mirror curvature is therefore not a limitation for future designs.

In controlling the devices, uniformity in the response of the mirrors is desired. If the response is sufficiently uniform, it would be possible to predict the response of all elements by characterizing any one of the mirrors. However, since the width of the springs is close to the resolution limit of the fabrication process, it is possible that there might be a distribution of the spring constant in the array. If the response between mirrors significantly differs, each mirror would have to be calibrated separately to produce the desired displacement. Fig. 10 shows a plot of displacement as a function of voltage for two mirrors. Within the noise levels of the measurement, both mirrors follow the same curve. Since only two mirrors have been measured and the measurement uncertainty is relatively high, more precise measurements are needed to establish a valid conclusion about uniformity of response.

To minimize optical signal loss the surface of the mirrors need to be highly reflective and the spacing between adjacent mirrors have to be minimal. Reflectivity of silicon is 50% at 300
Preliminary measurements show that the reflectance of the mirrors is about 45% at 400 nm wavelength, indicating that our MEMS mirrors will likely introduce lower optical losses compared to ordinary LC devices. The spacing between mirrors in the current design is relatively wide (10 µm) to avoid problems associated with stiction between adjacent devices. In future designs, the spacing can be kept to a minimum (2 µm) to avoid dead spots in the device.

V. CONCLUSION

An array of micromachined mirrors was designed and fabricated to be used for ultrafast pulse shaping at shorter wavelengths than it is possible with liquid-crystal devices. 400 nm piston motion was obtained at around the desired operation voltage of 10 V. The mirrors were designed to have a quick response time because of the small mass of the device and the comparably large spring constant. Based on preliminary measurements we did not resolve any cross-talk or any non-uniformity in response. However, more precise measurements are needed to give conclusive results.