Liquid deformable mirror for high-order wavefront correction

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We propose and demonstrate a novel liquid deformable mirror, based on electrocapillary actuation, for high-order wavefront correction. The device consists of a two-dimensional array of vertically oriented microchannels filled with two immiscible liquids, an aqueous electrolyte, and a viscous dielectric liquid, where the dielectric liquid overfills the top end of the channel and forms a thin layer on top. To remedy the poor reflectivity of pure liquids, a free-floating reflective membrane or a dye-coated liquid can be used. The proposed device offers several advantages for adaptive optics applications. These advantages include a high number of actuators, high stroke dynamic range, low power dissipation, fast response time, an initially flat surface, and low cost. However, the device is mainly suitable for dynamic wavefront correction and is limited by its orientation. © 2006 Optical Society of America

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In the field of adaptive optics, there is a growing demand for deformable mirrors with high spatiotemporal bandwidth, high stroke dynamic range, low power dissipation, and low cost.[1] Conventional deformable mirrors[2–4] that rely on the deformation of a thin plate or a membrane as a result of various actuation mechanisms (electrostatic, electromagnetic, and piezoelectric) suffer from low achievable spatial resolution, large actuator coupling, high power dissipation (this is true for some electromagnetic and piezoelectric actuators), large actuator hysteresis, and high cost. Liquid crystal devices can have high spatial resolution, but these devices are still slow for most adaptive optics applications. Liquid crystal devices also suffer from dispersion and polarization problems because they are transmissive correctors.

Liquid is a highly deformable medium compared with solid thin plates and stretched membranes. The use of liquid as a deforming medium for wavefront correction is not well studied, probably because of the low reflectivity of most liquids. However, by employing an unconstrained floating reflective membrane on top of the deforming liquid surface or by using a colloidal mixture of reflective nanoparticles,[5] the issue of low liquid reflectivity can be solved. So far, in the past decade only two liquid-based deformable mirrors have been demonstrated. These are based on electromagnetic actuation of mercury[6] or a magnetic liquid, such as a ferrofluid.[7] In this Letter we propose a novel liquid deformable mirror (LDM) based on electrocapillary actuation.

Figure 1(a) illustrates the concept of the proposed LDM. The device basically consists of a vertically oriented microchannel array. These microchannels are filled with two immiscible liquids, an aqueous electrolyte, and a viscous dielectric liquid, where the dielectric liquid overfills the top end of the channels and forms a thin layer on top. To remedy the problem of the low reflectivity of a pure liquid surface, a free-floating reflective membrane or a dye-coated dielectric liquid can be utilized. A self-assembling reflective colloidal film spread at the surface of the dielectric liquid[5] can also be employed to achieve a higher reflectivity. With this configuration, an initially flat surface is easily achieved.

A detailed diagram of a single channel is shown in Fig. 1(b). The inner wall of each microchannel consists of several layers of materials, apart from the bulk substrate. A layer of conducting material, which serves as an electrode, is deposited onto the bulk substrate and then coated with a thin layer of a dielectric. To vary the wetting behavior inside the capillary, a hydrophobic layer is applied onto the dielectric coating. The setup constitutes a cylindrical capacitor where the other electrode is connected to the electrolyte. The upward or downward flow of liquid inside the microchannel is facilitated by an electrocapillary pressure. This electrocapillary pressure is the result of the reduction of the interfacial energy between the wall and the conducting liquid when a potential difference between the electrolyte and the solid electrode exists. This electrocapillary pressure can be expressed as[8]

$$\Delta P = (2/d)(\epsilon_0 \epsilon_r/\tau)V^2, \tag{1}$$

where ϵ_0 is the permittivity in vacuum, ϵ_r and τ are the dielectric constant and thickness of the insulator, respectively, d is the diameter of the capillary, and V is the applied voltage. The outflow of liquid from the top end of the channel induces the deformation of the free-liquid surface. This deformation can be tuned for

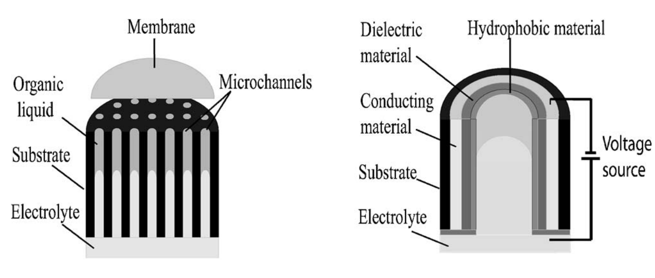

Fig. 1. Design concept of an electrocapillary actuated LDM: (a) mirror configuration, (b) single-channel profile.

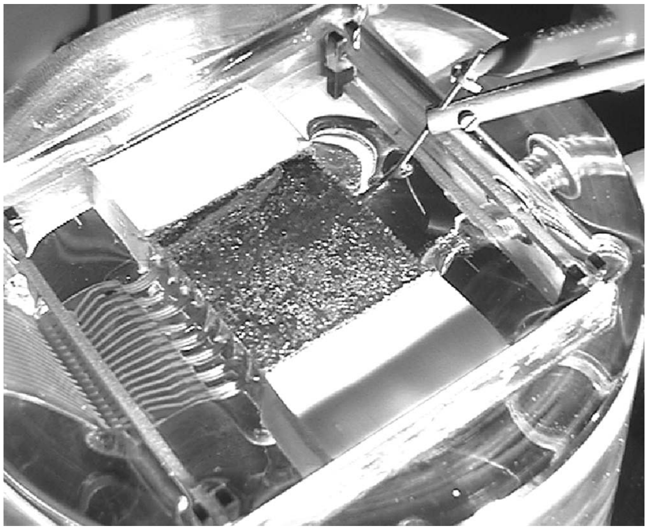

Fig. 2. Test device with an array of 64×64 microchannels.

correcting an aberrated wavefront. A push–pull actuation is realizable with this device, thereby enabling a higher degree of wavefront correction. The time scales for the upward and downward movement of the liquid inside the channel are of the same magnitude.[9]

The present electrocapillary actuation differs from the conventional electrocapillary[10] setup with the use of a dielectric coating on the solid electrode, an electrolyte instead of a dielectric liquid, and the presence of the hydrophobic material. In this present configuration, the flow of electrical current through the channel is prevented. Leakage current, which is negligible, occurs only in the dielectric material. The liquid–liquid interface inside the capillary initially forms a convex meniscus, due to the nonwetting property of the hydrophobic material, and in consequence the liquid movement inside the channel happens into two regimes. First, as the voltage is applied, the liquid–liquid meniscus inside will flip from a convex to a concave shape. After this meniscus inversion, bulk-liquid transport follows.

The fundamental issue of surface waves is addressed in the proposed device. Because the diameter of the microchannels is a few hundred micrometers and the actuator pitch is of the same order, the wavelength of surface ripples that can be present during operation is less than a millimeter. With this wavelength, the surface tension effect dominates over the influence of gravity, and the dispersion relation for surface waves[11] reduces to

$$f = \frac{\sqrt{(\sigma k^3/\rho)}}{2\pi}, \tag{2}$$

where f is the frequency, σ is the surface tension of the liquid, ρ is the density of the liquid, and k is the wavenumber ($k = 2\pi/\lambda$). The damping coefficient for surface waves is expressed as

$$\alpha = (2\eta k^2/\rho). \tag{3}$$

A damped wave is attained when $\alpha = 2\pi f$. Overdamping occurs when $\alpha > 2\pi f$. With the right viscosity of the dielectric liquid, these capillary waves can be damped out in less than a millisecond, given that the wavelength is less than a millimeter. Thus surface ripples will not pose any serious impediment to the dynamic operation of the LDM.

To validate the principle of the proposed device, we experimented on a test device[8] that has the same actuation mechanism previously discussed. Figure 2 shows the device immersed in a pool of two immiscible liquids (NaCl solution and n-hexadecane). The device consists of an array of 64×64 capillaries arranged in a hexagonal structure. Each individual capillary has a diameter of approximately 350 μm. The device is connected to a voltage source via a ribbon cable attached to the side wall of the structure. Electrical addressing of the array is done by grouping eight capillaries (nearest neighbor) together in a column. Thus there are eight electrodes attached to the device. This kind of addressing results in the actuation of a column of channels instead of an individual channel. Hence the determination of the influence function for a single channel is not possible with this device. This drawback is addressed in the prototype LDM, which is under construction.

We performed preliminary measurements to determine the temporal and spatial characteristics of the surface deformation. For these measurements, the floating reflective membrane was not used. The temporal measurement was conducted using a Lichtschnitt system.[12] A collimated laser beam was partially blocked by a knife edge and focused onto the surface of the liquid. The reflected beam was then recollimated and detected by a photodiode. For this measurement, NaCl solution and n-hexadecane were used. A Mach–Zehnder interferometer was used to study the shape of the surface deformation. A high-speed two-camera system was employed to capture successive frames. For the interferometric measurement, glycerol and silicone oil, with kinematic viscosity of 500 cSt, were used. These liquids were used to facilitate the measurement.

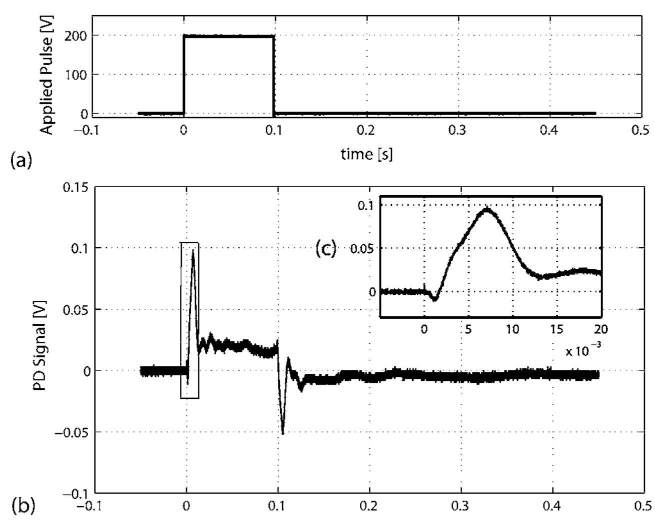

Fig. 3. Response time measurement: (a) applied pulse with amplitude of 196 V and duration of 100 ms, (b) rise time of the liquid surface, (c) enlarged plot of the boxed region.

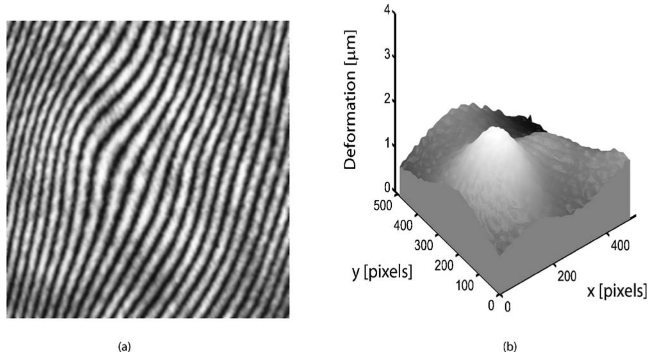

Fig. 4. Interferometric measurement of the surface shape: (a) interferogram, (b) reconstructed shape of the surface.

Figure 3 shows the result obtained from the temporal measurement.[12] A pulse with an amplitude of 196 V and duration of 100 ms [see Fig. 3(a)] was used as an input signal to the actuators. The rise time of the liquid surface is depicted in Fig. 3(b). The graph shows that the photodetector signal reaches its maximum before the end of the applied pulse. This maximum is then followed by an oscillatory movement, which may indicate that surface ripples were generated subsequent to actuation. The important observation that can be made from the rise-time measurement is that the maximum signal is reached at around 7 ms [see Fig. 3(c)]. This maximum signal corresponds to a surface displacement of about 1 mm. Figure 3(c) shows that a surface depression happens first before the surface rises. The height of this depression is roughly 140 μm and is reached at approximately 1 ms. This phenomenon may be due to the inversion of liquid–liquid meniscus inside the channel. This has been also observed previously.[13] The slope of the rise and fall of the surface bump is the same, as evident from the graph. Thus the time scales of the upward and downward actuation are of the same magnitude. For the temporal measurement, surface ripples are present because of the low viscosity of hexadecane, which is not sufficient to fully damp the capillary waves. In the final device, the viscosity will be appropriately chosen. The preliminary response time measurement indicates that the device can reach an operating frequency of 500 Hz or higher.

Figure 4 shows one intermediate frame of the shape evolution of the bump obtained from the interferometric measurement. Figure 4(a) shows the interferogram obtained from one of the cameras. Based on this interferogram, the phase can be retrieved and used to derive the shape of the actuated surface. The surface profile is computed by using

$$H(x,y) = \frac{\phi(x,y)\lambda}{2\pi[\cos(\theta_1 + \theta_2)]}, \qquad (4)$$

where $\phi(x,y)$ is the unwrapped phase, λ is the wavelength of the laser used, and θ_1 and θ_2 are the incident angle and angle of reflection, respectively. Figure 4(b) is the derived bump shape corresponding to the interferogram in Fig. 4(a). The result obtained shows that the stroke requirements for adaptive optics application (typically a few micrometers) can be easily met.

In conclusion, a novel LDM based on electrocapillary actuation of liquid inside a microchannel array is presented. The actuation principle was validated by using a test device. Initial measurements show that the device has a fast response time (of the order of milliseconds) and a large stroke dynamic range. The proposed device offers several advantages, such as a high number of actuators, large stroke dynamic range, low power dissipation, fast response, an initially flat surface, and reduced fabrication cost. Numerical modeling of the presented concept and further measurements using the prototype are in progress and will be presented in succeeding publications.

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