Piezo-driven deformable mirror for femtosecond pulse shaping

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We have developed a deformable, gold-coated mirror based on piezoelectric actuators with 15-μs response time. With 20 independent channels we were able to compress 72-fs pulses from a Ti:sapphire oscillator down to 45 fs in a 4f zero-dispersion compressor arrangement. Spectral interference was used to measure the mirror performance, while the spectral phase interferometry for direct electric field reconstruction (SPIDER) technique was used for the laser pulse characterization. © 2004 Optical Society of America

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Control of the phase of ultrashort laser pulses is a difficult yet enormously important issue in ultrafast optics. It is only since the introduction of pulse-shaping techniques that the bandwidth of chirped-pulse amplification systems has been fully exploited, and amplified pulses have reached the Fourier limit.[1–3] The whole domain of coherent control has been made accessible to researchers as a result of the development of pulse-shaping techniques.[4]

There are two approaches to spectral-domain pulse shaping. One relies on changing the spectral phase in separated regions (pixels). Liquid-crystal modulators[5,6] permit simultaneous control over both spectral phase and amplitude. Very-high-resolution systems with up to 640 channels have been demonstrated.[7] Since each pixel is controlled independently, complicated phase and amplitude masks can be applied, permitting fine pulse shaping. However, all liquid-crystal modulators suffer from slow response, radiation absorption, limited power handling capability, and gaps between the modulation stripes that give rise to satellite pulses. Another approach to pulse shaping facilitates the use of a deformable mirror or membrane. The reflecting surface of such a device is displaced by actuators. Each actuator causes a specific deformation mode to appear. One can place such a reflector in a suitable optical arrangement to translate the deformations into spectral phase modulation. In micromachined deformable mirrors a thin elastic membrane is suspended over an array of actuator electrodes.[8,9] When a potential is applied to an electrode, the membrane is deformed by Coulomb forces. Such a device suffers from a broad response mode to a single actuator extending over the whole membrane.

Another reported deformable mirror construction is a thin silicon wafer supported on a set of resistors that change length as their temperature changes as a result of Joule heat.[10] This design has serious drawbacks: the response is very slow (a few seconds), and there is a significant tremor that is present on a subsecond time scale. Mirrors driven by piezo elements have also been built, but their applications were limited to wave-front corrections. In Ref. 11 a round deformable mirror based on a bimorph piezo disk with a circular pattern of electrodes is described.

In this Letter we demonstrate femtosecond pulse shaping with a piezo-actuated deformable reflector (PADRE), a novel construction that combines fast response, good spectral resolution, and relatively low cost of fabrication. By virtue of its design, the reflector provides low loss and smoothly varying phase modulation.

Our deformable mirror is a rectangular glass plate measuring 50 mm × 12 mm × 0.5 mm that is attached to a row of 20 piezoceramic actuators, each of which can be controlled independently by voltage. The mirror was fabricated as follows: First, 12 properly polarized piezoceramic plates (PSI-5A4E Ceramic[12]) 50 mm × 15 mm × 0.5 mm were bonded together with pieces of fine stainless-steel mesh (electrodes) placed between them (see Fig. 1). High-strength epoxy resin was used to construct the stack. The piezo stack was then bonded to a 12-mm-thick glass block by the same epoxy, and the electrodes on each side of the stack were glued together with a conductive epoxy. Next, the piezo stack was sectioned into 20 separate actuators with a 0.4-mm-thick circular diamond saw, and the gaps between sections were filled with silicon adhesive. Finally, the top glass plate was bonded, polished to better than λ over 90% of the surface, and

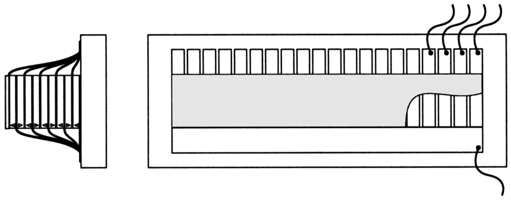

Fig. 1. Illustration of the PADRE. The device consists of a block of glass upon which 20 stacks of piezo elements are mounted in a row. Each stack consists of 12 layers. A 0.5-mm-thick plate of gold-coated glass is attached onto the top.

gold coated. The thick supporting glass plate and high-strength adhesives ensured that the structure as a whole was quite rigid, and the soft silicon minimized parasitic coupling between the sections, at the same time providing proper electrical insulation. Voltages as high as 300 V could be safely applied to individual actuators.

According to the manufacturer's data, a 300-V potential applied to our stack elongates it by 1.4 μm. This would correspond to 7π phase retardation at 800 nm for the mirror. However, because of the coupling between the neighboring actuators that results from the top plate, the actual range of the mirror surface displacement resulting from a single actuator action is smaller and extends over a broader region. A Michelson interferometer was used to determine the actual performance of the PADRE. The mirror was placed in one arm of the interferometer and the fringe pattern change as a result of different sets of voltages applied to the actuators was recorded. From the fringe pattern we calculated the displacement of the mirror surface as a function of the position along the mirror. First, we verified experimentally that by application of small bias voltages ($<30\%$ of maximum) to the actuators the mirror surface can be flattened with accuracy limited by our diagnostic method. Then, two measurements were performed. In the first measurement a single actuator was driven with maximum voltage (300 V). The measured mirror surface displacement resembles a bell-type curve with a height of 1.0 μm and width of 3.8 mm (FWHM) corresponding to ~ 1.5 times the single section width. The response time for a voltage step was measured to be 15 μs. In the second measurement the voltage alternated between 0 and 300 V for consecutive actuators. The resulting surface deformation can be well approximated with a sine function with amplitude of 0.3 μm. Ideally, the top glass plate should be as thin as possible to minimize the coupling between adjacent actuators. However, polishing such a plate poses a serious challenge. We believe that the plate thickness in our reflector (0.5 mm) is a good compromise, although we have not attempted a systematic study of this particular design aspect.

In experiments with femtosecond pulses we used a spectral phase modulator with the PADRE reflector in the focal plane of a $4f$ zero-dispersion compressor consisting of a 600-groove/mm ruled grating and a 0.5-m focal-length mirror (Fig. 2). In this setup the optical path for different frequencies can be controlled by appropriate deformation of the reflector, and the pulse's electric field E_{in} is modified by addition of a spectral phase

$$E_{\text{out}}(\omega) = E_{\text{in}}(\omega)\exp[i\phi(\omega)], \tag{1}$$

with $\phi(\omega) = 2\omega d(\omega)/c$, where E_{out} is the output pulse field, ω is the optical frequency, c denotes the speed of light, and d is the mirror displacement.

First we measured the response function of the PADRE by means of the spectral interference technique, using a Michelson interferometer with a modulator in one arm. The signal recorded by the spectrometer is

$$I(\omega) = I_0(\omega)\{1 + \cos[\omega_0\tau + \phi(\omega)]\}, \tag{2}$$

where I_0 is the spectral intensity of the input pulse, ω_0 is its central frequency, τ is the delay between the modulated and the reference pulses, and ϕ is the phase introduced by the modulator. By means of the algorithm typically used in spectral phase interferometry for direct electric field reconstruction[13] (SPIDER) we reconstructed $\phi(\omega)$ from the measured interferogram. The response function of a single actuator measured with this method, shown in Fig. 3, is consistent with the results obtained from cw interferometric measurements. In addition, we verified that the total deflection of the mirror surface is a linear combination of each actuator response function.

To test the PADRE performance for pulse shaping we stretched the pulses from a homemade Ti:sapphire oscillator to 72 fs by passing them through a 76-mm-thick block of fused silica. The pulses were characterized by a SPIDER apparatus.[13] After propagation in the dispersive medium the pulses acquire a predominantly quadratic spectral phase of $2700/\text{PHz}^2$. The pulses were sent to the compressor setup described above, and the pulse length was minimized during successive iterations with the spectral phase measured

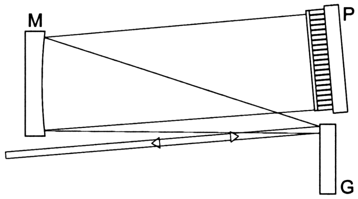

Fig. 2. Compressor setup. The incoming beam of femtosecond pulses is diffracted by a 600-groove/mm grating G (the point of incidence coincides with the focal plane of the concave mirror), then each spectral component is focused with a 50-cm focal-length concave mirror M on the PADRE (P) surface placed in the mirror focal plane. Retardation of each frequency depends on the local deformation of the PADRE.

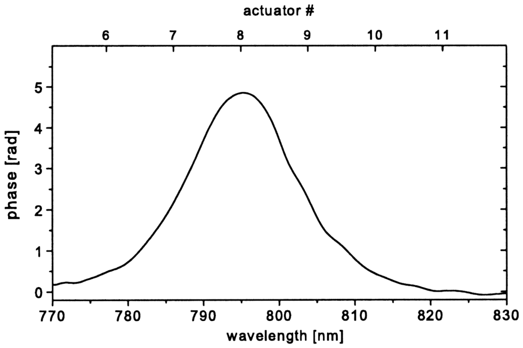

Fig. 3. Single actuator response function—measured spectral phase difference $\phi(\omega)$ introduced by a single actuator. The FWHM width is 16 nm, corresponding to a 1.8 actuator period. The positions of the actuators' centers are marked on the top axis.

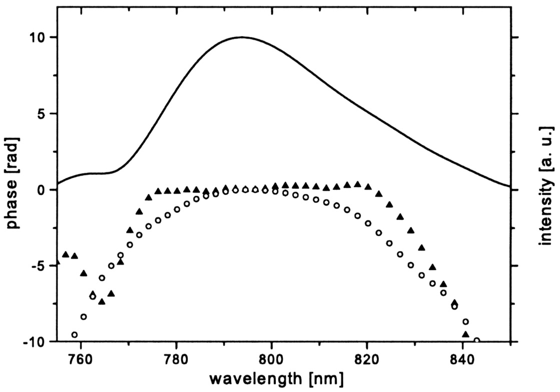

Fig. 4. Measured pulse spectrum (curve) and spectral phase (open circles) of the stretched pulse from a femtosecond oscillator and spectral phase after compression (filled triangles). Kinks in the retrieved phase of the compressed pulse come from SPIDER errors in the regions of low spectral intensity.

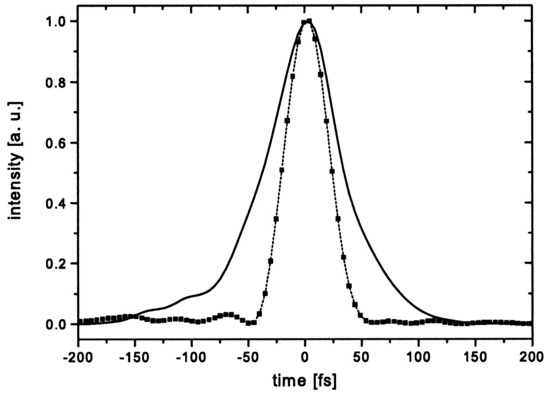

Fig. 5. Measured temporal profile of the pulses before (thick curve) and after (dotted curve with squares) compression.

with SPIDER used as real-time feedback. The results are presented in Figs. 4 and 5, together with the pulse measured before the compressor. We were able to flatten the phase in a 24-nm-wide region about the central wavelength to within 0.4 rad. As one can see from Fig. 4, the phase shows significant variation in the wings of the laser pulse spectrum. We attribute this to large errors introduced by SPIDER for lower spectral intensities.

Our setup requires only a few actuators to cover the region where the spectral intensity of the pulse is significant. This is because to avoid spectral clipping we built the 4*f* compressor so that the whole pulse spectrum, including its weak wings, fits the PADRE. However, higher resolution can be achieved if some spectral clipping is allowed. The resolution of the mirror in the sense of its capability of reproducing complex phase functions (i.e., complex surface shapes) depends on the ratio of the spectral bandwidth of the incident beam to the width of the response function. This ratio is a free parameter that can be easily adjusted by the 4*f* compressor arrangement. The PADRE can be scaled to larger dimensions. The only requirement is that the glass block supporting structure be rigid enough. Also the individual actuator can be made narrower.

In conclusion, we have demonstrated a deformable mirror based on piezoceramic actuators. With its compact design and straightforward extension to a desired mirror length, the deformable mirror can provide a direct replacement for existing chirped-pulse amplification systems in stretcher setups, offering a significant decrease in the amplified pulse duration. The mirror has a narrow response function and provides a fast (several microseconds) response. The deformable glass plate can be coated with any metal or dielectric layers. Because PADRE relies on piezoelectric elements, it suffers from all the drawbacks typical of such devices, such as hysteresis and creeping. These defects are, however, irrelevant in all systems operating with a feedback loop.

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