The deformable mirror method of adaptive phase correction

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Received May 16, 2003

In this paper, a simple method of phase correction by using a micromachined deformable mirror (MMDM) is demonstrated. With correction of high-order phases due to propagating through medium, we obtained a clean pulse shape, flattened spectral phase and decreased the femtosecond laser pulse duration. It is shown by our experiment that the deformable mirror is an effective and easy method for adaptive phase correction.

OCIS codes: 320.2250, 320.5550, 140.4480.

With the development of ultrafast laser system, people pay attention to the pulse quality to enhance the performance of systems. Though femtosecond oscillators are able to provide nearly dispersion-free pulses, those fs pulses often get group-delay dispersion after passing through amount of material in the amplifier stage. The dispersion broadens the pulse duration and causes sidelobes in the intensity distribution of the pulse. People who require ultrashort clean pulses have to find method of dispersion compensation. Up-to-date great improvements have been developed in pulse dispersion compensations. Those techniques can be divided into passive schemes and adaptive schemes. Passive schemes are always based on gratings, prisms, chirped mirrors, and their combinations[1]. Though these techniques sometimes are quite accurate, they are always complex to adjust. Spatial light modulation (SLM) is one of the adaptive ways for dispersion[2,3]. SLM always includes a liquid-crystal spatial light modulator in the Fourier plane of a zero-dispersion line. Its main drawback is a limited dynamic range because of the characteristics of the mask used in the modulator. Verluise *et al.*[4] demonstrated an acousto-optic programmable dispersive filter (AOPDF). It can achieve arbitrary dispersion and wavefront control by coupling the laser pulse and a longitudinal traveling acoustic wave. AOPDF systems require high quality of optical elements and thus are expensive. Recently several experiments have attracted people's interest on phase compensation by using a micromachined deformable mirror (MMDM)[5,6]. The deformable has been used for wavefront control. But now its ability of spectral phase correction is getting more and more notice. The most advantage of the deformable mirror is its nearly zero-loss and continuous change characteristic. And it is easy to control and cheap compared with SLM and acoustic-optics systems.

Here we used the deformable mirror to correct the phase distortion due to propagating through common K9 glass, and measured the results by the SPIDER technique[7].

Figure 1 shows the structure of the MMDM. The deformable mirror is in fact a 8×24 mm^2 silicon nitride membrane coated with gold. The membrane is suspended over a linear array of 19 electrodes channel used as control actuator. A control voltage applied to the control actuator creates an electrostatic attraction between the membrane and the electrode, distorting the mirror surface. According to Ref. [3], the mirror surface deflection δd depends linearly on the square of the applied voltage V_l, that is

$$\delta d \propto V_l^2. \tag{1}$$

Here the control voltage is applied to the lth control actuator. Then we can have the control signal C_l for the lth channel of the MMDM as

$$C_l = V_l^2. \tag{2}$$

It is assumed there is a mirror influence function $\phi_l(x,y)$ for the lth channel. The total surface deflection of the MMDM is the linear combination of influence function for all actuators. That is

$$\Delta S(x,y) = \sum_{l=1}^{p} C_l \phi_l(x,y), \tag{3}$$

where $\Delta S(x,y)$ is the mirror surface deflection. For the same voltage applied to different actuator, the surface deflection is not the same. The whole deflection of the mirror causes the light to travel a different path, changing the spectral phase in the area of the deformation. The total phase difference is given as

$$\phi = 4\pi \Delta z / \lambda. \tag{4}$$

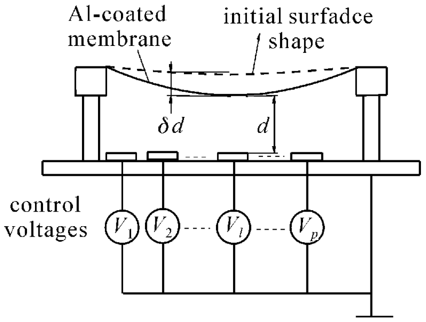

Fig. 1. Schematic structure of MMDM.

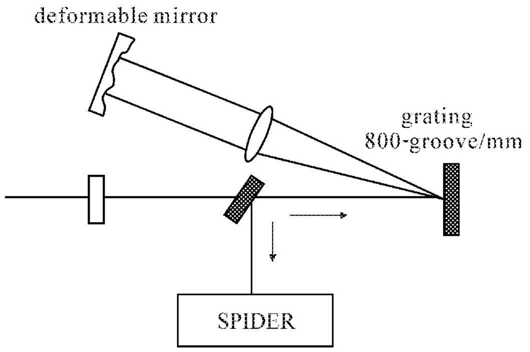

Fig. 2. Experimental setup of the deformable mirror stretcher.

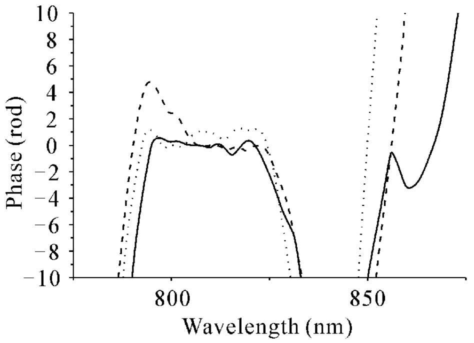

Fig. 3. SPIDER result of spectral phase correction by deformable mirror. The dotted line is the phase of the original pulse. The dashed line is the phase of the pulse propagating through the K9 glass plate. The solid line is the corrected phase.

For our deformable mirror, the maximum deflection is 8 μm, resulting in a phase of 40π at 800 nm. This amount of phase compensation is adequate for most laser systems.

The experimental setup is shown in Fig. 2. The ultrafast laser pulse generated from kilohertz laser amplifier system, with pulse duration of 80 fs is input into a $4f$-zero-dispersion stretcher, consisting of an 800-groove/mm grating and a 35-mm focal-length lens. The spectral components of the pulse are mapped spatially onto the 24-mm width of MMDM. We can change the spectral phase of the pulse by changing the surface of the deformable mirror. The experimental result was measured by SPIDER.

We first calibrated the MMDM. We aligned the stretcher with a flat mirror, set the dispersion zero, and changed the flat mirror into the deformable mirror. We took the SPIDER result as the baseline phase with 0 V applied to all actuators. Then we applied the same control voltage to each actuator electrode. With control voltage applied to the lth actuator, the difference between the baseline phase and the result phase from SPIDER was the calibration of the lth actuator. As in Eq. (3), we can determine the influence function for each actuator electrode. Those influence functions can be used in feedback algorithms for adaptive phase control in the future. But in a very simple way, with the result of calibration, we can at least obtain the direction and the appropriate extent of phase correction in a single-step.

To test the effect of the deformable mirror, we put a 0.3-mm thin plate of K9 glass in the beam path, as shown in Fig. 2. According to the phase distortion shown by SPIDER result, different voltage was applied to MMDM to compensate the phase distortion. Figure 3 shows the spectral phase and Fig. 4 for the time-domain intensity.

As shown in Fig. 3, the original femtosecond pulse has some high-order dispersion after passing amount of material in the beam path of 1-kHz amplifier, with pulse duration of 88 fs. After propagating through the thin K9 plate, quadratic and cubic phases are apparently brought to the spectral phases, which caused pulse duration of 113 fs, together with several side lobes behind the main peak. The strongest side lobe was nearly 25% of the intensity of the main peak, which decreased the pulse contrast.

We applied about 6-V voltage to the 19th channel to correct the spectral phase, which results in the flattened output spectral phase within 1 rad peak-to-valley. The maximum phase correction was over 4 rads. We got a clean pulse shape with the pulse duration decreased from 113 fs FWHM down to 91 fs. In Fig. 4, the side lobes of the output pulse of the stretcher were almost eliminated. Using logarithmic scale to the intensity (Fig. 5), we can clearly find out that the MMDM improves the pulse by the method of redistributing the spectral components. It transferred the energy of the side lobes into the main peak instead of simply filtering the unwanted, and

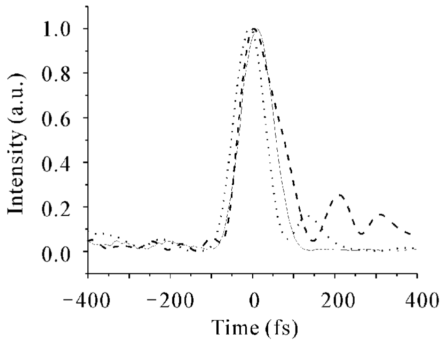

Fig. 4. The intensity of the pulses in time domain. The dashed line is the intensity of the pulse propagating through the K9 glass plate. The solid line is the one of the corrected pulse. The dotted line is the one of the original pulse.

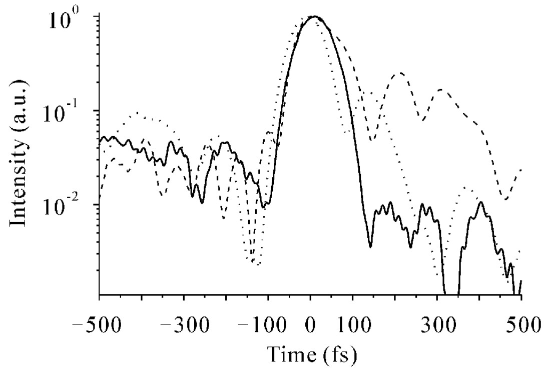

Fig. 5. Output pulse in a logarithmic scale. The dashed line is the intensity of the pulse propagating through the K9 glass plate. The solid line is the one of the corrected pulse. The dotted line is the one of the original pulse.

resulted in high pulse contrast. That is to say, the MMDM is a low-loss device.

There was still some incompletely compensated phase, especially at the ends of the spectrum. It was because of the thin lens we used in the stretcher, and it will be improved much if we turn to an all-reflective setup. Another reason may come from influence of the fluctuation of optical field on the measurement of SPIDER.

In conclusion, we demonstrated an effective method of phase correction by using of a deformable mirror. The direct idea for this deformable mirror method is to change the problem of spectral phase compensation to spatial optical path control. Since the spatial characteristic is very easy to control, this method is very attractive and promising. As to our results, SPIDER measurement shows that high-order phases in the pulse can be flattened to get no more than 1-rad peak-to-valley for spectral phase. The side lobes in time dependence intensity resulting from the high-order phases were eliminated effectively with phase correction by the deformable mirror. Sequentially we decreased the pulse duration and enhanced the pulse contrast. With feedback algorithm, the MMDM method is a very effective way of adaptive phase correction.

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