Effects of Mirror Surface Deformation in Optical Delay Lines Based on Resonant-Scanning Micromirrors

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Compact optical delay lines based on scanning micromirrors [1] have great potential for autocorrelation, femtosecond laser spectroscopy and Optical Coherence Tomography (OCT). Experimental data shows that rapid scanning optical delay lines (RSOD) have asymmetric profiles of the output optical pulses [2]. In this paper we report on measurements of the static deformation of the micromirror and show that the mirror shape is responsible for the observed asymmetric broadening of the delayed pulse.

The scanning time delay (Fig. 1) has the structure of the Michelson interferometer. A pulse train enters the system and is split into two beams in a 50/50 beamsplitter. One beam travels a fixed distance while the other beam's path contains the micro-optical delay line. Both beams are focused to a spot in a Beta Barium Borate (BBO) crystal, which produces an auto-/cross-correlation signal through second harmonic generation. The output signal is proportional to $\chi^{(2)}$, the second-order susceptibility of the BBO:

$$I_{cross}(\tau) \propto |\chi^{(2)}|^2 \int I_{shaped}(t)\cdot I_{ref}(t-\tau)\, dt$$

where τ is the relative delay time between the two pulses. For auto-correlation measurements $I_{shaped}(t)=I_{ref}(t)$.

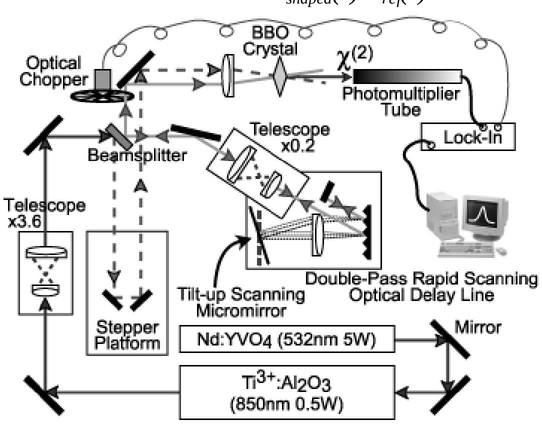

Fig. 1. Optical system diagram of the apparatus used in the generation and measurement of dynamic auto- and cross-correlations.

The delay line shown in Figure 1 is a double-pass rapid scanning optical delay line (DP-RSOD) [3]. Introduction of a scanning micromirror allows for compact and portable DP-RSOD geometries. Our surface micromachined polysilicon scanning micromirrors are fabricated by the MUMPs® process [4]. They are tilted up to an angle of 45º above the substrate by manually sliding a shuttle connected to the supporting frame of the mirror (Fig. 2 [5], [6]). The micromirrors are actuated by interdigitated electrostatic comb-drives. The residual stress gradients deform the mirror and frame as shown in Figure 4.

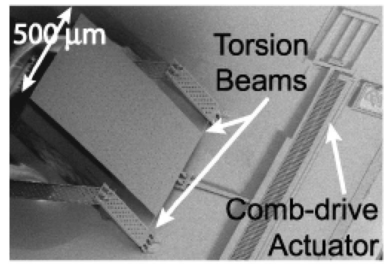

Fig. 2. Scanning electron microscope (SEM) image of tilt-up resonant scanning micromirror. The polysilicon mirror is 760µm high by 500µm wide by 1.5µm thick; supported on a frame by 2µm wide torsion beams; dynamically driven at 1060 Hz with an optical deflection of 16 degrees.

The RSOD is a special implementation of a femtosecond pulse shaper (FTPS) [7], in which the scanning micromirror takes the place of the spatially patterned mask in the Fourier plane (Fig. 3). The micromirror introduces a linear phase shift on the optical spectrum. The Fourier transform of this linear phase shift in frequency corresponds to a group delay in the time domain.

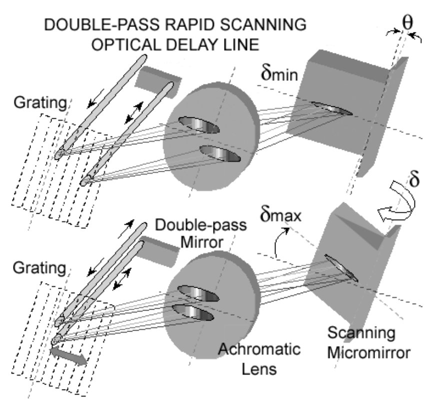

Fig. 3. Schematic of a double pass rapid scanning optical delay line with a scanning micromirror at minimum tilt-angle, δmin, and maximum tilt-angle, δmax.

In our system the grating and mirror are oriented such that the spectrum of the optical pulses are spread over approximately 0.5 mm along the C-D cut in Figure 4a. The mirror shape along C-D is shown in Figure 4c. Perpendicularly to the spectral spread, the optical pulses are focused to a FWHM of 24 µm.

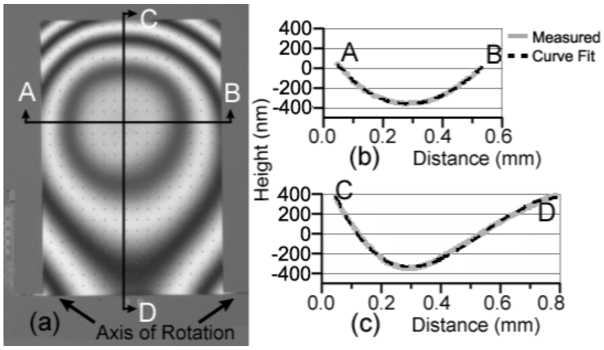

Fig. 4. (a) Interferogram of the tilt-up micromirror obtained by a Zygo NewView100 3-D Surface Profiler. (b) Surface profile along cut A-B with a measured radius of curvature at of 7.22 cm. (c) Surface profile along cut C-D.

The C-D cut surface profile can be expressed by the following third-order polynomial fit:

$$P_{C-D}(x) = 4\cdot(-8.60\times10^{-9}\cdot x^3+3.26\times10^{-6}\cdot x^2+1.20\times10^{-3}\cdot x)$$

where $P(x)$ is the wavelength dependent optical path length in the DP-RSOD. The first order term corresponds to the tilt of the mirror, the second order term accounts for symmetric pulse broadening, and the third order term dictates the asymmetric pulse broadening. In our experiment, we compensate for the second order term by adjusting the mirror position, a customary technique in ultrafast optics.

Passing through the DP-RSOD pulse shaper (Fig. 5), each spectral component experiences a phase shift each time it approaches and is redirected from the micromirror as a function of the distance from the Fourier plane $y = P(x)$,

$$\phi(L,\omega)_{DP} = 4\cdot\omega\cdot L/v_p(\omega) = 4\cdot(\omega/c)\cdot P(x)$$

where $\phi(L,\omega)$ is the wavelength and path length dependent phase shift and $v_p(\omega)$ is the phase velocity.

The third order Taylor expansion of the spectral phase for narrow spectrum signals centered at ω_0,

$$\phi(\omega)\approx \phi_0+(\omega-\omega_0)\phi'+(1/2!)(\omega-\omega_0)^2\phi''+(1/3!)(\omega-\omega_0)^3\phi'''$$

defines the group delay as $t_g(\omega_0)=(\partial\phi/\partial\omega)|_{\omega=\omega_0}$, the group velocity dispersion as $GVD(\omega)=\partial^2\phi(\omega)/\partial\omega^2|_{\omega=\omega_0}$, and the third order dispersion term as

$$TOD(\omega)=(1/6)(\omega-\omega_0)^3\partial^3\phi(\omega)/\partial\omega^3|_{\omega=\omega_0}$$

For an RSOD with our curved micromirror we calculate:

$$TOD = -4.94\times10^{-41}(\omega-\omega_0)^3\sec^3$$

The output pulses from the RSOD are then given by

$$E'(t) = F^{-1}\{F\{E(t)\}\exp(j\cdot\phi(\omega))\}$$

where $F\{E(t)\}$ is the Fourier transform of $E(t)$ and $\phi(\omega)=TOD$.

Figure 5b demonstrates the expected TOD output shaped pulse with the calculated phase variations shown in Figure 5a assuming hyperbolic secant input pulses ($E(t)\propto sech(t/\tau)$ where the FWHM, Δt_p, is given by $\Delta t_p=2\cdot\ln(1+(2)^{1/2})\tau$).

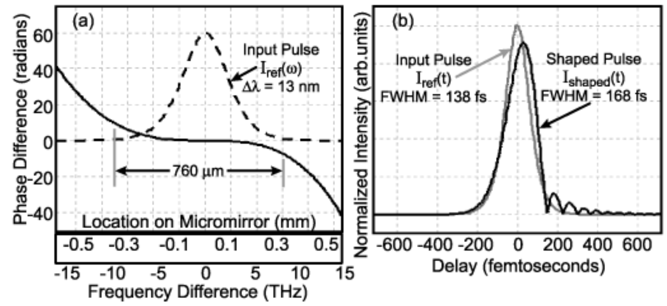

Fig. 5. Calculated third-order phase shift in the RSOD caused by the surface profile of the micromirror (a), and (b) a transform limited input pulse and TOD broadened output pulse from the RSOD.

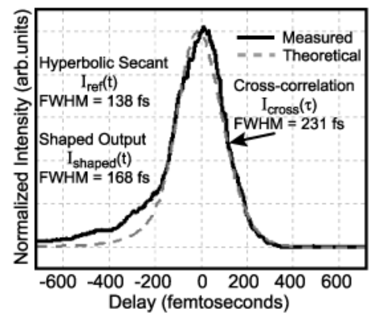

Fig. 6. Cross-correlation taken with the micromirror on the Fourier plane of the rapid scanning optical delay line.

Figure 6 shows the measured cross correlation of the input and shaped pulses. It is compared to the theoretical prediction based on a 138 fs input pulse and the 168 fs shaped pulse of Fig. 5b. The good correspondence of the measured and calculated cross-correlations verifies that TOD, caused by micromirror surface deformations, is the dominant pulse broadening mechanism in our RSOD. The micromirror surface deformations must therefore be carefully controlled in practical RSOD applications like femtosecond laser pulse shapers, optical delay lines, and OCT systems.

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