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Low-aberration high-speed-compatible optical delay line

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Abstract

We describe a simple approach to dispersion-free optical delay line design that provides very low aberration over an extended delay range. In this approach, we minimize aberrations by directing non-axial beam displacements along a line of symmetry built into the apparatus. We show improved performance and significant reduction of wavefront aberrations by comparing simulation and experimental results with a similar delay line that lacks this line of symmetry. The new design facilitates transform-limited recovery of spectral resolution in Fourier transform coherent anti-Stokes Raman scattering, and accordingly, we demonstrate 3.5 cm^{-1} spectral resolution with a 10 ps delay scan range.

Many linear and nonlinear optical methods such as interferometry and pump–probe spectroscopies require optical delay of one light path with respect to the other. Delay line performance requirements vary with application but are particularly demanding when dealing with broad spectral ranges and ultrafast pulses, especially if rapid scanning is necessary. The requirement of matched dispersion for the delayed and reference beams, encountered when working with very short pulses, generally requires a dispersionless free-space delay line. In such arrangements, optical paths are mechanically modulated.

Mechanical path modulation is easily accomplished at low speed with linear motion of a reflecting mirror along the optical axis. Such arrangements introduce no significant aberrations, but they are limited in scan rate by inertial constraints on mirror acceleration. Repetition rate can be increased by replacing linear motion with oscillatory or rotational motion of a reflecting surface [1–6]. These configurations also suffer from various drawbacks, such as a low duty factor [2], significant static wavefront distortion from uncompensated reflections at curved surfaces [4,6], difficulty in fabrication [7], or off-axis beam displacement [1,3,5]. The latter can be partially compensated for by using dispersive elements [1,3,8], but this limits the usable light bandwidth. When not compensated for, the off-axis displacements lead to delay-dependent wavefront aberration [5].

In applications such as broadband Fourier-transform coherent anti-Stokes Raman scattering (FTCARS) [9–12], rapidly repeating, dispersion-free pulse delay on the order of several ps is required. In this Letter, we describe a simple, dispersion-free optical delay line that provides very low aberration over a delay range of at least 10 ps. The design compensates

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for delay-dependent off-axis beam displacements by directing them along a line of symmetry introduced with a cylindrical mirror. Two implementations of this design are presented: one based on a galvanometric mirror and one based on a rotating mirror, the latter taking full advantage of the symmetry and potentially achieving much faster scan rates.

Comparing simulations of these two implementations with a previously reported design [5,12], we show that simply introducing this line of symmetry significantly reduces static and delay-dependent wavefront distortions. We confirm simulation results with experimental measurement of beam deviation and FTCARS signal generation for galvanometer designs with and without this line of symmetry.

Figures 1(a) and 1(b) give an example layout of a reduced-aberration delay line where optical path changes are induced by a change in mirror angle (θ_g) of a galvanometer. A collimated beam is sent on the edge of the galvanometer mirror, at a distance h_g from its rotation axis. A cylindrical mirror is placed so that the surface of the galvanometer mirror at $\theta_g = 0$ contains its focal axis. A return mirror is also placed at the focus of the cylindrical mirror [as shown in Fig. 1(b)], in order to return the light along the optical path.

From the projection in Fig. 1(a), we see that the beam is deflected at an angle $2\theta_g$ from the galvanometer mirror. At the cylindrical mirror, it is reflected along a path that is quasi-parallel with the z axis, as long as θ_g is small. As θ_g becomes large, the light sent to the cylindrical mirror from the galvanometer will appear to originate away from its focal line, so it will not be reflected parallel to the z axis and will not be returned along its original path. This shows up as a delay-dependent wavefront x -tilt in Fig. 2, right column. In order to minimize this effect, we minimize the required θ_g for a given delay τ by making ϕ_g as small as possible.

The y - z plane projection in Fig. 1(b) shows two beam colors representing light paths at different galvanometer mirror displacements. The beam displacement in this plane follows the symmetry line of the cylindrical mirror so that no path-length-dependent aberrations are introduced by the off-axis beam translations in the y - z plane. As it rotates, the galvanometer mirror moves along the incoming light path as $r_Z = h_g \tan(\theta_g)/\sin(\phi_g)$, and reflects the light to a displacement-dependent point on the cylindrical mirror.

Light reflected from the cylindrical mirror is returned by a mirror that, in the design shown, has to be tilted slightly away from a plane parallel with the cylindrical mirror ($\alpha_g - \beta_g$) in order to send the light back along its original path in the y - z plane. This means that the optical path between the cylindrical mirror and retro-reflecting mirror changes slightly with path delay. Accordingly, the return mirror plane cannot contain the focal axis of the cylindrical mirror at all delays, and there is a slight, delay-dependent astigmatism (wavefront x -curvature in Fig. 2). This effect can be minimized by optimizing α_g to reduce the difference $|\alpha_g - \beta_g|$, which requires ϕ_g to be closer to $\pi/2$.

Optical delay generated by galvanometer rotation is essentially linear for small angles ($\approx \pm 5^\circ$) and is given as

$$\Delta l(\theta_g) = 2h \frac{\tan(\theta_g)}{\sin(\phi_g)} \left[1 + \frac{\sin(\gamma_g) + \sin(\alpha_g - \beta_g - \gamma_g)}{\cos(\alpha_g) + (1 + \sin(2\phi_g)/\sin(\alpha_g))} \right], \quad (1)$$

where $\gamma_g = 2\theta_g + \alpha_g - \pi/2$.

The two sources of aberration can be mutually minimized with appropriate limits on ϕ_g that depend primarily on the cylindrical mirror curvature, the beam offset h_g , and beam diameter. These limits on ϕ_g are largely relaxed with the polygonal mirror design.

Figures 1(c)–1(f) give an example layout of a reduced-aberration delay line using rotation of a polygonal mirror through some angle θ_p to change path length. A cylindrical mirror is placed so that the loci of intersections between the incoming beam and the rotating mirror surface form a line coincident with the cylindrical mirror focal line. As with the galvanometer design, a return mirror is also placed at the cylindrical mirror focus, but displaced away from the polygonal mirror [as shown in Fig. 1(f)], so that the line-focused beams reflected along the z direction by the cylindrical mirror are returned along the optical path. Here, the light deflected by the polygonal mirror always originates at the cylindrical mirror focal line, and no aberrations arise from the moving mirror. Some delay-dependent aberration (primarily astigmatism) does arise if $\phi_p \neq \pi/4$ since, in this case, $\alpha_p \neq \beta_p$, as discussed above.

Figure 1(d) shows the path traced by the intersecting light as the mirror rotates. The position differential in the plane of the facet is given by $R_p[1 - \cos(\theta_p)]$, where R_p is the distance between the mirror's rotational axis and the axis of light impinging on the polygonal mirror. Accordingly, the differential path length given by the intersection of the facet and the light beam along the z axis is given by $h = R_p[1 - \cos(\theta_p)] \tan(\phi_p)$.

Optical delay in the polygonal mirror design is approximately parabolic in θ_p , and given by

$$\Delta l(\theta_p) = R_p[1 - \cos(\theta_p)] \tan(\phi_p) \times \left[1 + \frac{\sin(\gamma_p) + \sin(\alpha_p - \beta_p - \gamma_p)}{\cos(\alpha_p) + (1 + \sin(2\phi_p)/\sin(\alpha_p))} \right], \quad (2)$$

where $\gamma_p = 2\theta_p + \alpha_p - \pi/2$.

For both scanner designs, it is desirable that divergence of the beam does not change much over the delay range of the apparatus, and that the beam size remains small compared to the area of the reflective surfaces. The former calls for a small beam divergence and long Rayleigh range (z_R), thus a large beam size, opposing the latter requirement. Generally, one can find design parameters that will satisfy both constraints, and the desired delay range largely sets the parameters for these competing needs.

Based on simulations performed using the Optica plug-in to Mathematica (Wolfram), we determined that a 50 mm focal length cylindrical lens and 2 mm spot diameter were appropriate for a 10 ps delay range with a central wavelength of 1080 nm. The total path length for both galvanometer and polygonal mirror arrangements was 100 ± 10 mm, much shorter than $z_R = 0.75$ m, yielding no significant delay-dependent divergence.

Figure 2 shows wavefront simulations at delays of 0 and -1 mm (-3.3 ps round trip) for outputs of the two designs displayed in Figs. 1(a), 1(b) (Cyl/Gal) and 1(c)–1(f) (Cyl/Poly), and for a similar galvanometer-based delay line using a spherical mirror (Sph/Gal), first introduced by Liu *et al.* [5]. Sph/Gal uses a spherical mirror, so it lacks the line of symmetry introduced here with the cylindrical mirror. Otherwise, it contains the same components as, and is arranged similarly to, Cyl/Gal. Optical component positions and angles were optimized to minimize wavefront aberrations for all simulations. The optimized delay line parameters are given in Table 1. Those found for Sph/Gal correspond closely with Ref. [5].

Wavefronts calculated for each of the three scanners at zero delay show some astigmatism, i.e., they have different wavefront curvature along the x and y axes. For the Cyl/Gal and Cyl/Poly layouts shown in Fig. 1, delay-dependent astigmatism is negligible, and the static (zero delay) astigmatism dominates, even though it is also quite small ($<0.2\lambda$). In contrast, both static and delay-dependent astigmatisms are significant for the Sph/Gal design. Here, the astigmatism arises from arrangement of the spherical mirror. Because $\phi = 0$, the beam impinging on the spherical mirror neither originates from nor is focused to the focal point of the mirror. Astigmatism across the beam ranges from $\approx \lambda$ at zero delay to $\approx 2.5\lambda$ at -1 mm delay, changing sign, axis, and amplitude.

Wavefront tilt (asymmetry in the profiles around the $x = 0$ or $y = 0$ point) varies significantly between scanner designs. Cyl/Gal and Cyl/Poly show negligible tilt at zero delay, and between them, only Cyl/Gal has a change in tilt with delay. For the Sph/Gal design, tilt changes significantly with delay. At -1 mm (delay = -3.3 ps round trip) tilt has changed by 2.5 over the beam diameter.

The wavefront plots clearly suggest that implementation and exploitation of a symmetry line along which off-axis beam deviations can be directed facilitate dramatically improved wavefront profiles at both delay positions shown. In fact, compared to the previously published Sph/Gal design, reduction of beam displacement by $\sim 10\times$ and tilt by $\sim 1000\times$ is achieved for the designs introduced here. Some spherical aberration, field curvature, and higher-order aberrations are present. On the other hand, because they are $\ll \lambda$ over the entire beam diameter, they are not expected to significantly impact performance of the design for interferometry.

The major improvement illustrated here is due to the fact that the cylindrical mirror has a focal line instead of a focal point. Both the scanning mirror and the back reflection mirror can be placed on this focal line, ensuring minimal geometric aberrations. The scanners take further advantage of the cylindrical symmetry by matching the direction of beam translation with the cylindrical mirror focal axis.

In order to demonstrate the utility of the scanner designs we have introduced, we embedded the Cyl/Gal (or, for reference, the Sph/Gal) scanner into an FTCARS arrangement similar to that in Refs. [10,12]. In each case, 40 fs pulses from a Coherent Fidelity ($\lambda = 1073$ nm, repetition rate = 73 MHz) were split, with one arm passing through the delay scanner. A 20 Hz ramp wave was used to drive a Thorlabs GVS111 galvanometer to ± 5 deg. The delayed and reference arms were co-linearly recombined, and 1.5 nJ pulses from each were focused

to $w_0 = 3 \mu\text{m}$ into CS_2 . The first pulse generates a vibrational coherence. The second pulse also generates a coherence, which interferes with the first at varying time delays. The degenerate four-wave mixing (DFWM) signal of the second pulse then generates an interferogram over the static background from the DFWM of the first pulse. The anti-Stokes DFWM signals were isolated using a 1010 nm shortpass filter, and detected using a Thorlabs APD410C avalanche photodiode as a function of scanner delay. The signal was low-pass filtered and sampled at 2 MHz, giving 10^5 points per interferogram. The laser bandwidth was just sufficient to excite the 655 cm^{-1} ν_1 symmetric stretch of CS_2 , which has a natural linewidth of $<1 \text{ cm}^{-1}$ [13].

The left-side inset of the top panel in Fig. 3 shows a DC-subtracted FTCARS signal transient obtained using the Cyl/Gal scanner. The time-zero signal extends to an amplitude of 20 on this scale but is truncated for clarity. The main part of the top panel displays a portion of the FTCARS signal intensities at delay times ≈ 5.7 ps, using the Cyl/Gal and Sph/Gal scanners, showing that the Cyl/Gal signal fringe oscillations are about 2X stronger at this delay time. Simulations and experiment suggest that the smaller signal from the Sph/Gal scanner could be due to strongly delay-dependent wavefront tilt leading to poor beam overlap at long delays.

In order to evaluate delay-dependent beam overlap, we focused the beam exiting the scanner at zero-delay to $10 \mu\text{m}$ with a 50 mm focal length lens. We then placed a $10 \mu\text{m}$ pinhole at the focus, and measured light throughput as a function of scanner delay. The right inset of the top panel in Fig. 3 shows beam transmission for the Sph/Gal scanner to be roughly 50% that of the Cyl/Gal scanner at 5.7 ps delay, accounting for the observed drop in FTCARS signal. We note that Ideguchi *et al.* [10,12,14] used the Sph/Gal delay line for FTCARS, and published in Fig. 2 of Ref. [14] a delay-dependent signal intensity that closely mimics the Sph/Gal pinhole transmission curve shown here. Thus, we surmise that the low Sph/Gal signal level at larger delays is not likely due to misalignment.

The lower panel in Fig. 3 shows Raman spectra retrieved from Fourier transforms of FTCARS interferograms generated in CS_2 using Cyl/Gal and Sph/Gal delay lines. Both interferograms were carried to delay times long enough to achieve a resolution of $\approx 3.3 \text{ cm}^{-1}$ (delay ≈ 10 ps). The recovered {peak widths, signal-to-noise ratios} for the ν_1 peak were $\{3.5 \text{ cm}^{-1}, > 200\}$ and $\{33 \text{ cm}^{-1}, < 20\}$ from the Cyl/Gal and Sph/Gal designs, respectively. The $\approx 30 \text{ cm}^{-1}$ resolution we obtain with the Sph/Gal scanner is consistent with the FTCARS spectral resolution obtained with this scanner design in the past [10,12,14,15].

We note that Sinjab *et al.* [12] have recently achieved improved effective resolution with the Sph/Gal design by using Matrix Pencil [16], a post-acquisition signal estimation. Here, we have retrieved spectra with only a Fourier transform and no signal estimation. Of course, Matrix Pencil or similar estimation could also be applied to signal from the Cyl/Gal or Cyl/Poly scanners we have introduced to further improve effective resolution.

We have introduced a design for dispersion-free delay lines with static and delay-dependent wavefront aberrations that are sufficiently small to allow transform-limited performance over a delay range of at least 10 ps, supporting a spectral resolution of $\approx 3.5 \text{ cm}^{-1}$ for FTCARS

and similar experiments. To our knowledge, this is the first time a dispersion-free high-speed-compatible delay scanner has demonstrated transform-limited performance over such a large scan range.

Wavefront aberrations are minimized in these designs by inducing a line of symmetry (here, with a cylindrical lens). Off-axis beam displacements associated with varying time delays are, to the extent possible, directed along this symmetry axis. While we have demonstrated this scanner design only with a non-resonant galvanometer operating at 20 Hz, we designed the delay lines to be compatible with high-frequency delay modulations, and any resonant galvanometer operating at much higher frequencies [17] is a drop-in replacement. The Cyl/Poly design is compatible with even higher scan rates, as polygonal mirrors [3,12,18] have been used to achieve scan rates up to 50 kHz. Simulation results suggest that Cyl/Poly design should perform even slightly better than the Cyl/Gal since the former's delay-dependent aberrations are smaller.

We expect this scanner design to facilitate significantly improved fingerprint coherent Raman microscopy [19,20]. Most of the biologically relevant information in a Raman spectrum is found in the fingerprint where peaks are congested narrow ($<5\text{ cm}^{-1}$ width), making them unresolvable with present high-speed mechanical delay lines. We gratefully acknowledge the National Institute of Standards and Technology for use of the Fidelity laser.

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Fig. 1.

Optical delay line designs. In each case, incoming light propagates along the z axis. (a), (b) x - z and y - z projections of a delay line utilizing a cylindrical mirror and galvanometer (Cyl/Gal) with light and dark paths indicating different galvanometer positions. (c)–(f) Delay line utilizing a cylindrical mirror and a rotating polygonal mirror (Cyl/Poly). (c) Polygonal mirror design, with direction of incoming light. (d) The path incoming light traces across the mirror facet during scanner rotation. (e), (f) Angular deflection and translational displacement of the beam at discrete θ_p values in the x - y and y - z planes, respectively. Light and dark paths represent distinct mirror rotations. 3D schematics are available in Visualization 1, and Visualization 2.

Fig. 2.

Simulated wavefronts for the two delay line designs, Cyl/Gal and Cyl/Poly, displayed in Figs. 1(a), 1(b) and 1(c)–1(f), respectively, and for Sph/Gal, a previously published design [5]. The wavefronts are plotted for the reference delay (0 mm, top row) and for a delay of -1 mm, bottom row. The vertical axis corresponds to the optical axis, in units of wavelength. The other two axes are the x and y axes, in mm.

Fig. 3.

Measurements from the Cyl/Gal delay line (black) and the Sph/Gal delay line (red). Top panel: (left inset) FTCARS time trace recording for Cyl/Gal. (right inset) Light transmission through a $10 \mu\text{m}$ pinhole as a function of delay after passing through a Cyl/Gal or Sph/Gal scanner. (main figure) Late time section of FTCARS time trace from Cyl/Gal and Sph/Gal scanners. Bottom panel: 655 cm^{-1} ν_1 symmetric stretch of CS_2 shown from Cyl/Gal and Sph/Gal scanners.

Table 1.Angles Used in Simulations and Experiments, in Degrees^a

	ϕ	θ_0	α	β	h (mm)	R_p (mm)
Cyl/Gal	70	0	-20	0	8	
Cyl/Poly	55	0	-90	-70		50.8
Sph/Gal	90	20	20	0	8	

^aThe definitions of α and β for the (Sph/Gal) scheme are those in Ref. [5].