Supplemental Document

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Compact and adjustable compensator for AOD spatial and temporal dispersion using off-the-shelf components: supplement

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1. SUPPLEMENTAL DISCUSSION

A. Spatial Chirp

When a single dispersive element is used to compensate for AOD spatial and temporal dispersion, the arrangement introduces a small amount uncompensated spatial chirp: different wavelength components of the pulse are spread in space. In laser scanning multiphoton microscopy, these components are all recombined at the focal spot, so the spatial chirp is mainly significant if it distorts the beam shape so that the beam is clipped by apertures in the imaging system, including the back aperture of the objective, or if scattering in the medium between the objective and the focus is severe and path dependent [1].

Note that in this section, spatial chirp to refers to the extra spread in the size of the collimated laser beam following the AODs, even when the angular dispersion of the AODs is exactly compensated.

A.1. Spatial chirp is inherent in the compensation scheme

Negative GDD is created by propogating and angularly diverging beam through space. This results in a spread of the beam, Δw, which is a property of the angular divergence, $\frac{\partial\theta}{\partial\lambda}$, the amount of GDD to be compensated, and the bandwidth of the laser, $\Delta\lambda$.

$$\Delta w = L\frac{\partial\theta}{\partial\lambda}\Delta\lambda \tag{S1}$$

$$L = GDD/\left(\frac{\lambda^3}{2\pi c^2}\left(\frac{\partial\theta}{\partial\lambda}\right)^2\right) \tag{S2}$$

$$\Delta w = GDD\cdot\frac{2\pi c^2}{\lambda^3}\left(\frac{\partial\theta}{\partial\lambda}\right)^{-1}\Delta\lambda \tag{S3}$$

Pulse compressors, e.g. in laser cavities, are often constructed from 4 prisms or used in a double pass configuration, where the second pass reverses the spatial chirp, in order to avoid this effect. No such reversal is possible in schemes that use a single element to compensate for both spatial and temporal dispersion of the AODs.

For near infrared lasers with pulse durations on order or greater than 100 fs and large aperture AODs, the spatial chirp is generally small compared to the beam size and can be neglected. Our compensation scheme does not affect the spatial chirp.

A.2. Spatial chirp in a system without a telescope

After the initial compensating element, the beam direction is dispersed along one axis by a spread of angles $\Delta\theta$. After traveling a distance L to reach the first AOD, the beam is spread by an amount

$$\Delta w_0 = L\Delta\theta = L\frac{\partial\theta}{\partial\lambda}\Delta\lambda = L\theta_c\frac{\Delta\lambda}{\lambda} \tag{S4}$$

L is chosen to compensate the temporal dispersion of the AOD and is a property of the AOD independent of the choice of compensating element, as is the central deflection angle: θ_c. The spatial chirp is therefore a property of the AOD and the bandwidth ($\Delta\lambda$) of the laser.

$$\Delta w_0 = \text{GDD}_{\text{AOD}} \left((\sqrt{2}) \cdot \theta_c \right)^{-1} \left(\frac{2\pi c^2}{\lambda^2} \right) \Delta\lambda \tag{S5}$$

where the $\sqrt{2}$ applies if two orthogonal AODs are used. For the system described in the main text (GDD $\approx$ 15000 fs^2, $\lambda = 0.97\ \mu$m, $\frac{\Delta\lambda}{\lambda} = 0.011$, $\theta_c = 75$ mrad), the resulting beam spread is 0.91 mm, compared to the 9 mm aperture of the AODs.

A.3. Introducing a telescope does not change the spatial chirp

Our system introduces an telescope with spatial magnification M between the compensating element and the AODs. This has no effect on the amount of spatial chirp at the AODs. To see this, consider a system in which the first AOD is at the back focus of the telescope. In this case, the distance between the rear focus and the AOD, $L_3 = 0$ and the distance between the compensating element and the front telescope focus is $L_1 = \frac{L}{M^2}$, where L is the distance required when no telescope is used. Using $\left(\frac{\partial\theta}{\partial\lambda}\right)_{\text{element}} = M \left(\frac{\partial\theta}{\partial\lambda}\right)_{\text{AODs}}$, we find that Δw_1, the beam spread at the front focus is

$$\Delta w_1 = \frac{L}{M^2} M \left(\frac{\partial\theta}{\partial\lambda} \right)_{\text{AODs}} \Delta\lambda = \frac{\Delta w_0}{M} \tag{S6}$$

where Δw_0 is the magnitude of the spatial chirp without the telescope.

The telescope has a spatial magnification of M, so Δw_{final}, the spatial chirp at the AODs, is M times the spatial chirp at the front focus of the telescope.

$$\Delta w_{final} = M \Delta w_1 = M \frac{\Delta w_0}{M} = \Delta w_0 \tag{S7}$$

B. Limitations on ultra-short pulses

Three effects limit the bandwidth and hence the minimum duration of the laser pulses used in this system. The most significant is the residual angular dispersion, which limits the maximum deflection from the center and hence the field of view.

Spatial chirp spreads the different wavelength components of the collimated laser beam in one direction on the back aperture of the objective. This results in power loss and temporal pulse shape distortion. In our system and most others that would be used for scanning, spatial chirp is a minor effect compared to the residual angular dispersion.

Third order dispersion (TOD) lengthens and distorts the shape of ultra short pulses. For most scanning systems, including ours, TOD becomes significant only for very short (<40 fs) pulses.

B.1. Residual angular dispersion

As with all systems based on AOD scanning, we can compensate perfectly for angular dispersion only at one particular spot, which is chosen to be at the center of the field of view. Figure S1b shows the residual angular dispersion throughout the scan range and in particular at the edges, where it is most extreme.

When scanning a spot a distance x from the center, the residual angular distortion is

$$\Delta\theta = \left(\frac{\partial\theta}{\partial\lambda} - \frac{\partial\theta}{\partial\lambda}|_{\theta=\theta_c} \right) \Delta\lambda = \frac{\theta - \theta_c}{\lambda} \Delta\lambda = \frac{x}{f_{obj}} \frac{\Delta\lambda}{\lambda} \tag{S8}$$

and so the spot is distorted by an amount

$$\Delta x = f_{obj} \Delta\theta = x \frac{\Delta\lambda}{\lambda} \tag{S9}$$

This is independent of the focal length or NA of the objective, and remarkably also of the properties of the AOD.

In two photon fluorescence microscopy, excitation is proportional to the intensity squared, and the resolution of the microscope is determined by the square of the intensity point spread function (PSF). Taking into account also the two dimensional scanner and the diffraction limited spot size (w_0), the FWHM of the intensity squared PSF along the long axis of the elliptical spot (w) at a scan location (x, y) from the center is [2]

$$w = \sqrt{w_0^2 + \frac{1}{2} \left(\frac{\Delta\lambda}{\lambda} \right)^2 (x^2 + y^2)} \tag{S10}$$

In our system ($\frac{\Delta\lambda}{\lambda} = .011$, max deflection = 100 μm, $w_0 \approx 500$ nm), the long axis of the ellipse at the corners of the FOV would be 1.2 μm.

If the pulse duration were reduced to 50 fs ($\frac{\Delta\lambda}{\lambda} = .029$), the long axis of the ellipse would increase to 2.9 μm at the corners of the FOV. Alternately, if we wished to keep the ellipse long axis under 1.2 μm, the field of view would be reduced from ± 100 μm to ± 38 μm.

Angular dispersion compensation over the field of view has been demonstrated using specially fabricated optics [3]. Absent this special compensation mechanism, residual angular dispersion is the principal limit to using ultra-short pulses in AOD-based multiphoton microscopes.

B.2. Spatial Chirp

As discussed above, the spatial chirp is proportional to the bandwidth. Spatial chirp is detrimental if apertures in the system remove some wavelength components, which will increase the pulse duration and reduce the overall intensity. This can be corrected by decreasing the beam diameter through the AODs [1], at the cost of increased spot size or decreased scan angle, depending on whether the beam is magnified after the AODs to maintain filling of the objective back aperture.

In the system described in the main text, the spatial chirp elongates the beam on the back of the objective by 10%, while residual angular dispersion elongates the PSF by a factor of 2.4. This is typical of most systems: the detrimental effects of residual angular dispersion exceed those of spatial chirp.

B.3. Third order dispersion

Most materials (including TeO_2 deflectors) have a positive ratio of GDD (group delay dispersion: $\frac{\partial^2\Phi}{\partial\omega^2}$) to TOD (third order dispersion: $\frac{\partial^3\Phi}{\partial\omega^3}$). Angular dispersion following a grating creates negative GDD and positive TOD. Therefore, compensation of GDD with a grating always *increases* TOD. Prism-based compensation schemes can decrease TOD, while AOMs, like static gratings increase TOD.

The ratio of TOD to GDD due to angular dispersion from a grating is

$$\frac{\text{TOD}}{\text{GDD}} = -\frac{3\lambda}{2\pi c}\left(1 + \frac{2}{3}\frac{\lambda}{d}\frac{\sin(\theta_R)}{\cos^2\theta_R}\right) \tag{S11}$$

where θ_R is the angle of transmission relative to the normal of the grating.

For $\lambda = 0.97\mu$m, $\frac{3\lambda}{2\pi c} = 1.54$ fs. The ratio of TOD to GDD for TeO_2 is about 0.32 fs. The total TOD after the AODs' GDD is compensated is therefore approximately

$$TOD = \text{GDD}_{\text{AOD}} \cdot \left(1.9\text{ fs} + 1.6\text{ fs} \cdot \frac{2}{3}\frac{\lambda}{d}\frac{\sin(\theta_R)}{\cos^2\theta_R}\right) \tag{S12}$$

The inclusion of a telescope increases the TOD more than in grating/AOM based systems without a telescope, because d is smaller and θ_R larger, so the second term contributes more. For our system, the second term is about 0.38 fs, while in a system with our AODs but with no telescope the second term would be < 0.01 fs. Therefore including the telescope increases the TOD in our system by about 20% (from 1.9 fs $\times$ GDD to 2.28 $\times$ GDD). As the minimum pulse width scales like the cube root of the TOD, this increases the minimum pulse width by 6%.

As a rule of thumb [4], the pulse shape becomes distorted when $TOD \approx \frac{3}{4}\tau_0^3$ and the $\frac{1}{e}$ pulse width doubles when $TOD \approx 3\tau_0^3$. In our system, there are approximately 15,000 fs^2 of GDD from the AODs to correct. Using a grating/AOM without a telescope (and including the TOD of the AODs) would result in approximately 28,500 fs^3 $=$ (30.5 fs)^3 of TOD. In our system, there would be approximately 34,000 fs^3 $=$ (32.5 fs)^3 of TOD. In both cases, TOD would have a negligible effect on pulse duration for pulses for bandwidth limited pulses longer than 40 fs.

C. Comparison to using an AOM for compensation

Two types of dispersive elements have been used for precompensation: prisms and acousto optic devices. Compared to prisms, acousto optic devices allow for simpler tuning of the deflection angle without beam expansion or further reflective losses, but they introduce additional complexity, cost, and GDD to be compensated. In this work, we use a volume holographic phase grating coupled with a telescope. Both acousto optic devices and fixed gratings operate by diffraction, but there are key practical differences between our design and compensators using a third acousto optic device. In this section, we discuss these differences.

C.1. Cost and lead-time

Acousto-optic devices are expensive, and their cost increases with the aperture size. The acousto-optic device (we will assume it to be an AOM for brevity, but an AOD could also be used) used for compensation must have an aperture equal to that of the deflectors. It should operate at a carrier frequency 1.4 ($\sqrt{2}$) times as high as the frequency of the single deflector. In principle, there are slightly different design constraints on the AOM (which should maximize transmission over a narrower range of deflection angles) than on the deflectors (which should maximize the range of deflection angles, and hence the scan range), but these are unlikely to greatly influence the cost, which is related to the size of the crystal and the transducers required to drive it. Thus, including the AOM likely increases the cost of the whole system by $\sim$ 50%, in the range of \$5,000-\$15,000, depending on the aperture. The RF synthesizer and amplifier required to drive the AOM will also add about \$1,000. The lead-time on custom acousto-optic devices can be up to 6 months. This may not be a concern if the three acousto-optic devices are ordered as a custom-made set, but if deflectors are already available (e.g. can be re-purposed from a decommissioned device) or if a stock XY deflector can be delivered quickly, this additional lead time can add a significant delay.

Off the shelf volume holographic gratings are available in a range of line pitches for \$300-\$1000. The grating used in this work was \$745. The lenses and housing for the beam expander cost around \$300. All parts were in stock and shipped the next day.

C.2. Temporal dispersion and spatial chirp

As the AOM is sized similarly to the AODs, its inclusion increases the amount of GDD to be compensated by 50%. This increases the required separation between the dispersive element and the AODs and also the spatial chirp by the same amount. Replacing the AOM with a grating therefore reduces spatial chirp by 33%.

In addition to a 33% reduction in length due to elimination of the AOM, the grating/telescope combination allows for an even shorter path due to the region of enchanced negative GVD between the grating and telescope.

C.3. Adjusting temporal dispersion

Using a grating with a telescope allows for fine-tuning of the GDD by simple translation of the telescope. In this work, this translation was achieved by rotation of a lens tube in its housing. This simplifies the initial assembly and alignment and also allows adjustment if new components are added to the beam path. The AOM compensator, like the prism compensator, requires movement of the AOM followed by realignment to change the temporal dispersion.

C.4. Wavelength selection flexibility

An advantage of the AOM-compensated system is the possibility of maintaining perfect angular dispersion compensation without mechanical adjustment of components while changing the laser wavelength. If the AOM and AODs are all operated at a fixed central angle of deflection, the AOM angular dispersion can exactly cancel the angular dispersion of the AODs at the central angle for all wavelengths. This requires decreasing the driving frequencies of the AOM and AODs with increasing wavelength and creates a mismatch between the central angle of deflection and the Bragg angle that increases with greater change in wavelength.

While the AOM compensator can maintain perfect angular compensation across a range of wavelengths, bandwidth limited pulses can only be achieved at a single wavelength. If the AOM deflection angle is held fixed, the negative GVD scales as $\frac{1}{\lambda^2}$, while the material dispersion of the acousto-optic elements scales differently. In order to achieve perfect GDD compensation, the AOM must be translated and subsequently realigned to change the distance to the AODs.

With a diffraction grating, it is not possible to achieve perfect angular compensation at a fixed deflection angle across multiple wavelengths. However, it is possible to achieve perfect angular compensation by tilting the grating and adjusting the angle of incidence. This can be done so that the ray diffracted from the grating travels along the same path regardless of wavelength. Thus only tilt adjustments are required for angular compensation when the wavelength changes. Following tilt adjustments, the pulse width can be minimized by translation of the telescope, without movement of any other parts.

In summary, compared to the AOM, full compensation of both angular and temporal dispersion following a wavelength change is simpler using the grating/telescope system (other than small translations of the telescope, only tilt adjustments are required), but the AOM based compensator allows for *on the fly* wavelength changes while maintaining full angular and some temporal dispersion compensation.

If on the fly wavelength changes and full temporal compensation are desired with AOMs, one might adopt a "best of both worlds" approach by inserting two identical KTs back to back between an AOM and AODs. The first KT shrinks the beam, increasing angular divergence, and the second expands it, restoring beam size. Millimeter scale translation of one KT with respect to the other tunes the GDD and can be accomplished relatively quickly using a motorized translation stage.

2. SUPPLEMENTAL FIGURES

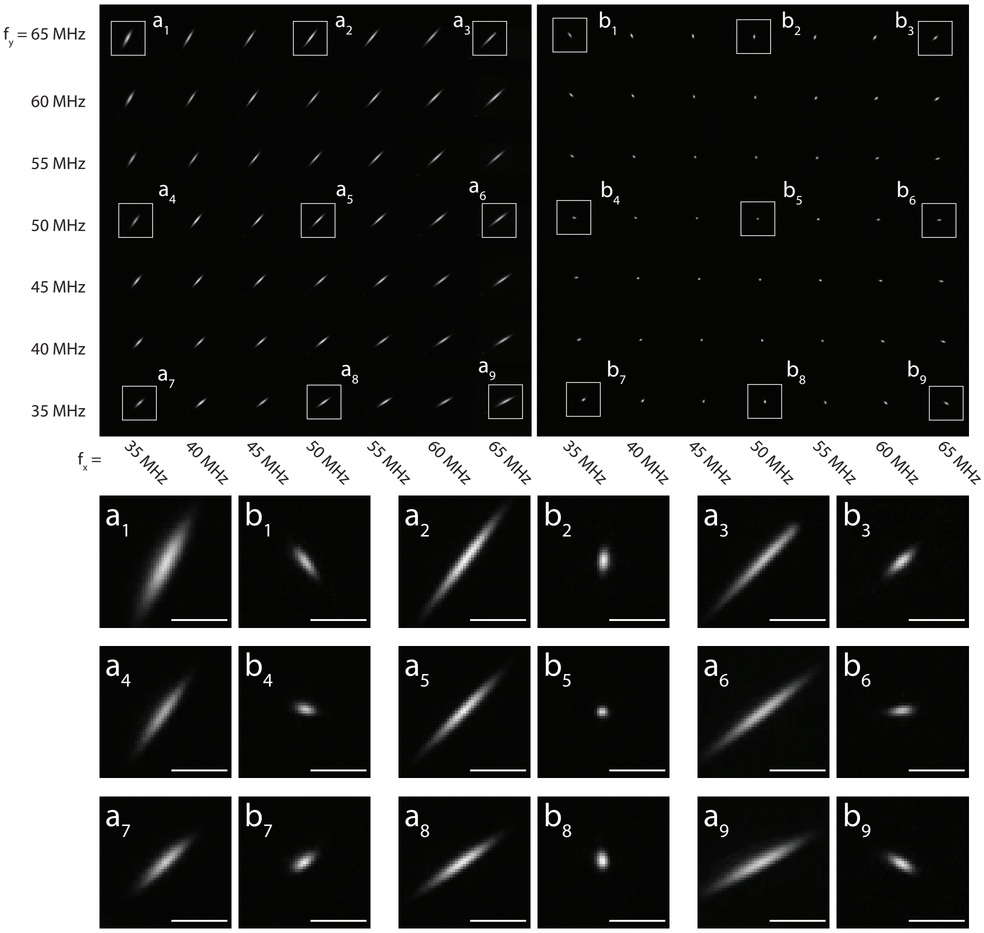

Fig. S1. Laser beam spots scanned for 35 − 65 MHz range with 5 MHz increment and recorded on a camera, with (right, b) and without (left, a) dispersion compensator. The beam was focused with a $f = 100$ mm lens onto a sensor with 4.8 μm pixels. Lower images show magnified images of the beam spots at the indicated frequencies/locations. Scale bar = 1 mrad (100 μm on detector)

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