Quartic-phase limited grism-based ultrashort pulse shaper

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By replacing the dispersive element in a zero-dispersion pulse shaper with a grism, we have constructed a quartic-phase limited pulse shaper. We demonstrate compensation of 4500 fs^2 without the use of a dynamic element in the pulse shaping line, which is approximately the amount of dispersion induced by a typical multi-photon microscope. We also demonstrate that detuning the pulse shaper to compensate for quadratic phase induces negligible spatial chirp, thereby maintaining a high quality focal spot for a microscopy setup. © 2007 Optical Society of America

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Pulse-shaping is playing a more extensive role in multi-photon microscopy.[1,2] As such, there is a need for high throughput pulse shaping systems that can be used in conjunction with only a laser oscillator (avoiding the use of amplifiers). Functionally, most microscopes introduce 3000 – 5000 fs^2 of dispersion. This must be compensated by an additional prism compressor (further complicating the system) or by using the pulse shaping line (using up valuable dynamic range). In this Letter we introduce a grism-based pulse shaper that addresses both of these issues for the first time. We also show that this setup does not introduce appreciable spatial chirp, making it optimal for microscopy applications.

To construct a pulse shaper with inherent third-order dispersion (TOD) compensating properties, the diffraction grating in a zero-dispersion pulse shaping line is replaced with a grism (HORIBA Jobin Yvon, model C524.28.090.45) consisting of a 45°-45°-90° BK7 prism in optical contact with a 1480 line/mm reflective diffraction grating. The unshaped pulse is dispersed with this element before being collimated (i.e. individual frequencies focused) with a 10-cm-focal-length achromatic lens onto a 1×4096 element, linear, reflective, liquid crystal spatial light modulator (LC SLM) provided by Boulder Nonlinear Systems. The pulse is then reflected back through the lens and onto the grism where the spectral content is spatially recombined to generate the shaped pulse. This is represented schematically in Fig. 1. It is important to note that the output pulse is slightly lower (approx. 1 cm) than the input pulse, and that this height change is accomplished with the lens and LC SLM.

The grism used in this apparatus has a single-pass throughput of 88–90% over 780–820 nm and is used near Littrow angle.[3] With a mirror in place of the LC SLM, we measure the throughput of the pulse shaping line to be 73%, close to the predicted value of 77%. We have previously determined the efficiency of the LC pulse shaper to be 85%.[4] Thus we obtain a predicted efficiency of 63%

for the pulse shaper. However, we measure a throughput significantly lower than this (55%) because the spectrum overfills the reflective area of the LC SLM, leading to clipping. To characterize the shaped pulses, we use the SEA TADPOLE[5,6] method to extract the spectral phase and intensity.

The zero-dispersion pulse shaping line is an ultrashort pulse compressor with a telescope of magnification $M=-1$ contained within it.[7] When the system is perfectly aligned, it may be viewed as a simple compressor with the grating separation set to zero. Thus it is possible to achieve either positive or negative group delay dispersion (GDD) by simply adjusting the grating separation in the pulse shaper. This allows one to compensate for residual GDD by slight misalignments of the pulse shaping line, preserving the dynamic range of the pulse shaping device and eliminating the need for an external compressor. Furthermore, because we are using a grism instead of a diffraction grating, we have a compressor that allows us to access the TOD as well. As one
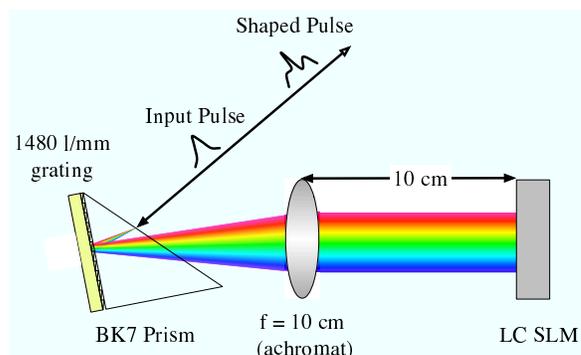

Fig. 1. (color online) Schematic representation of the grism-based ultrashort pulse shaper based on a zero-dispersion pulse shaping line.

can adjust the amount of TOD in a prism compressor by tailoring the insertion of the prism, the grism pulse shaper allows us to minimize TOD by adjusting the insertion of the grism. However, unlike a prism pair, the grism compressor can be adjusted to give the correct ratio of TOD/GDD.[3,8] Thus we can minimize both GDD and TOD from external dispersion sources by slight adjustments to the pulse shaping line, resulting in a pulse shaper that is limited to fourth-order dispersion (FOD). The dynamic range of the LC SLM is therefore preserved for tailoring the temporal pulse shape for our application.

To demonstrate the ability of the pulse shaping apparatus to compensate for GDD and TOD we use a metallic mirror in place of the LC SLM. We first use the pulse shaping line to compensate for the 670 fs^2 directly from the oscillator. We then insert 10 cm of BK7 glass into the pulse shaping beam (single pass) and adjust the insertion of the grism such that the TOD is minimized. This is possible because the grism is designed to provide a negative TOD,[3] while the BK7 induces positive TOD. Next, we move the achromat and mirror in tandem to minimize GDD as well, leaving us with a quartic-phase limited SEA TADPOLE image, an example of which is shown in Fig. 2. In order to compensate for the 4500 fs^2 and 3200 fs^3 from the BK7, we moved the lens and mirror 510 μm, and changed the insertion of the grism 175 μm. Note that in Fig. 2 we are also compensating for the GDD of the pulses directly out of our oscillator, so we are compensating for a total GDD of approximately 5200 fs^2.
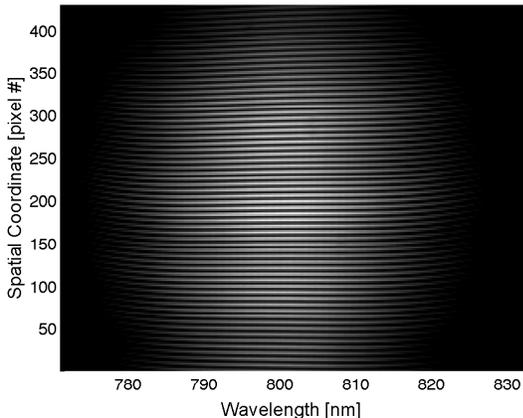

Fig. 2. SEA TADPOLE image with 10 cm of BK7 in the pulse shaping arm. The TOD and GDD are minimized by moving the lens and mirror in tandem and adjusting the insertion of the grism to provide the flattest fringes possible.

By comparing the extracted phases with and without the glass in the pulse shaping arm, we are able to extract the phase induced by the BK7, as well as the phase compensation due to the pulse shaping arm. These phases are shown in Fig. 3a. Figure 3b shows the extracted phase change due to the BK7 overlaid with the predicted spectral phase of the glass up to fourth-order in a Taylor series.
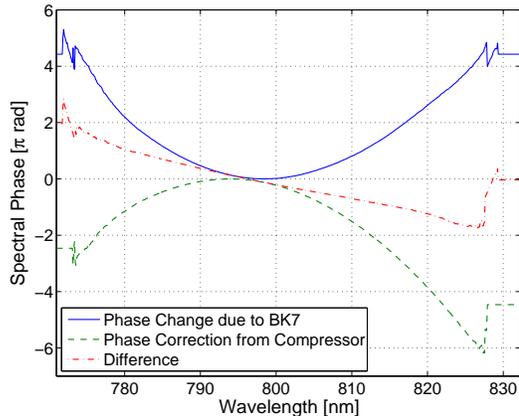
(a)
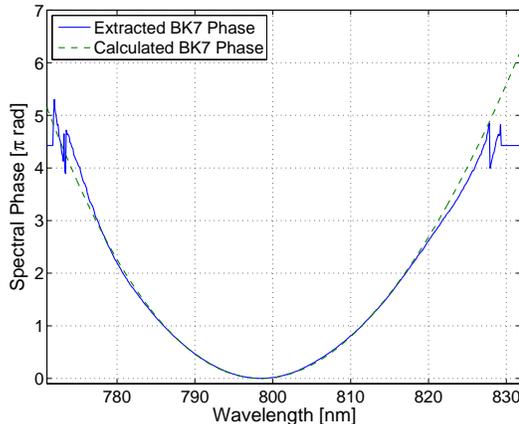
(b)

Fig. 3. (color online) (a) Phase change due to 10 cm of BK7 glass, as well as the phase correction induced by the grism pulse shaping line. (b) Theoretical dispersion due to 10 cm of BK7 glass with the extracted phase change due to the glass.

Because the adjustments to the setup required to remove GDD and TOD are so slight, spatial chirp from the apparatus is negligible. Using a commercial SHG FROG device (GRENOUILLE, Swamp Optics), we were able to determine the spatial chirp of the shaped output pulse before and after compensation of the external BK7 glass. Before correcting the phase, spatial chirp was measured to be -2.61×10^{-3} μm/nm, and after correction it was measured at -2.60×10^{-3} μm/nm. This indicates that the spatial chirp is negligible because the difference in the two measurements is within the experimental error from the GRENOUILLE. By comparison, the amount of spatial chirp before the 10 cm BK7 block was added to the pulse shaping line was measured to be -2.03×10^{-3} μm/nm, thereby demonstrating that the spatial chirp induced by a slight misalignment of the glass is greater that that due to misalignments in the pulse shaping line.

Also, by imaging the pulse shaping line in the far-field, we were able to determine that there is no appreciable spatial chirp due to the slight misalignments of the pulse shaper. This is an ideal result for microscopy applications, because it allows one to compensate for the 3000–5000 fs^2 of dispersion from outside optics without adversely affecting the focal spot in the microscope, as well as leaving the dynamic range of the pulse shaping device free for manipulation of the excitation pulses.

In order to demonstrate the pulse shaping capabilities of the setup, we then replaced the metallic mirror with the LC SLM. We have previously reported[4] that it is possible to achieve spectral phase and amplitude modulation with a single LC SLM, and that in doing so it is possible to experimentally determine the spectral resolution of the pulse shaping setup. Shown in Fig. 4 are some selected results extracted from the SEA TADPOLE images. In Fig. 4b, it can be seen that the spectral resolution of the pulse shaping apparatus is approximately 1 nm, a resolution that is quite good given that we have misaligned the pulse shaping line.

In conclusion, we have constructed and reported on what is, to our knowledge, the first grism-based ultrashort pulse shaper. Due to careful construction of the grism used as the dispersive element, the pulse shaping apparatus has a predicted throughput of 63%. We have also demonstrated that it is possible to eliminate the need for external pre- or post-compenstion of GDD and TOD by slightly misaligning the zero-disperion pulse shaping line. Altogether, we have constructed a high efficiency, programmable ultrashort pulse shaper, capable of compensating for dispersion due to external and internal sources of GDD and TOD. We feel that given this quality, and the fact that the majority of the dynamic range of the LC SLM is available for pulse shaping as opposed to dispersion compensation, this pulse shaping apparatus is optimal for applications such as multi-photon microscopy, where compensation of dispersion due to objectives is necessary, as well as the ability to control the temporal shape of the excitation pulse.[9]
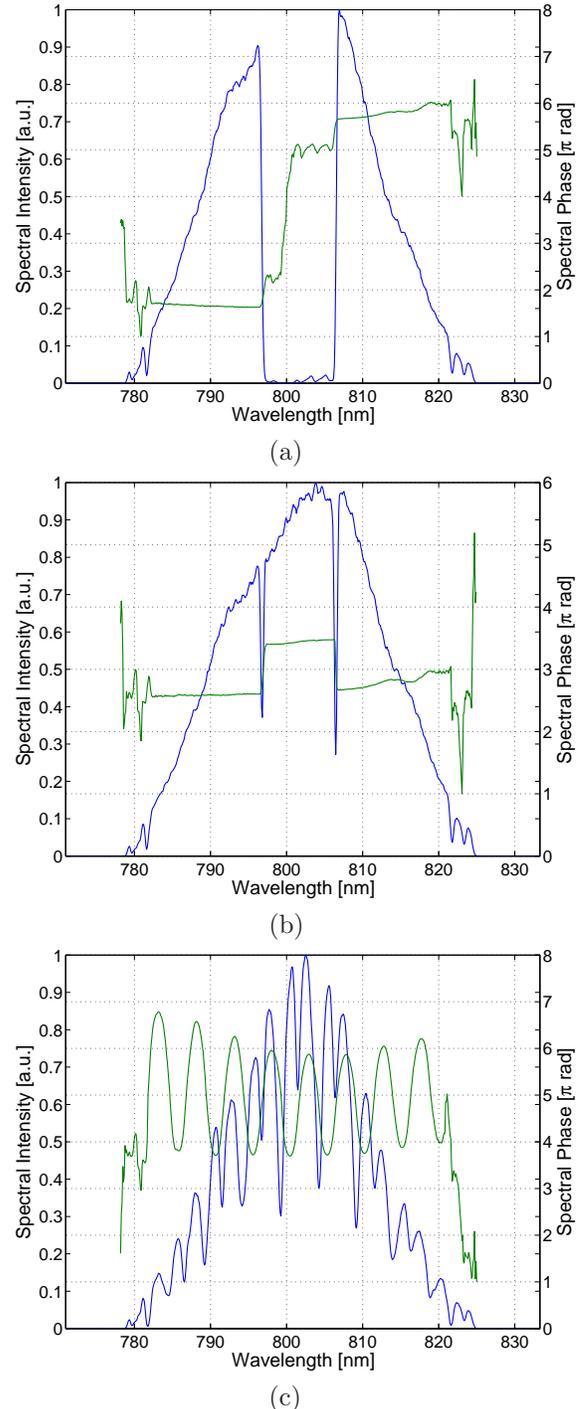
Fig. 4. (color online) (a) Amplitude modulation induced by the LC SLM. (b) Rectangular phase variations make it possible to determine the spectral resolution of the pulse shaper. (c) A sinusoidal phase variation written to a pulse which induces amplitude modulation as well.

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