Single-diffraction-grating and grism pulse compressors

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We introduce and demonstrate a simple, compact, and automatically aligned ultrashort-pulse compressor that uses only a single diffraction element—a grating or a grism (a grating on a prism). This design automatically has unity beam magnification and automatically contributes zero spatiotemporal distortions to the pulse, thus avoiding spatial chirp, angular dispersion, pulse-front tilt, and all other first-order spatiotemporal distortions. It is comprised of only three elements: a diffraction element, a corner cube, and a roof mirror. Half the size of comparable two-grating compressors, it can provide large amounts of negative group-delay dispersion with small translations of the corner cube. The device can operate on pulses with both large and small bandwidths by varying the corner-cube position. Using a grism as the diffraction element, material dispersion up to the third order can be compensated, and we demonstrated compensation for 10 m of optical fiber for 800 nm pulses. © 2010 Optical Society of America

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1. INTRODUCTION

An ultrashort pulse lengthens in time as it propagates through a dispersive medium, where lower frequencies of light propagate faster than higher frequencies. This effect, called group-delay dispersion (GDD), is undesirable in most applications, especially micromachining and multiphoton imaging, which thrive on the shortest possible pulses.

Only a few approaches exist for compensating for GDD and hence shortening the pulse to its transform limit. The most common is angular dispersion, which, independent of its sign, always yields negative GDD [1]. Prisms [2], gratings, and grisms (a diffraction grating written on a prism) [3] have been used. The amount of negative GDD is proportional to the square of the angular dispersion and the distance traveled by the pulse after the dispersing component.

Although angular dispersion introduces the desired negative GDD, angular dispersion itself is undesirable, and it also introduces undesired spatiotemporal distortions, spatial chirp, and pulse-front tilt, and thus is not generally useful by itself [4]. Useful pulse compressors based on angular dispersion necessarily require four identical dispersive components—the first to introduce angular dispersion (and hence negative GDD), the second to compensate for the angular dispersion, and the third and fourth to compensate for the spatial chirp after two prisms. A well-aligned pulse compressor, in principle, introduces negative GDD without the unwanted distortions of residual angular dispersion and spatial chirp and also without other spatiotemporal distortions, [4] such as pulse-front tilt, which typically accompany angular dispersion and spatial chirp.

Unfortunately, in practice, it is difficult to align—and maintained aligned—many of the commonly used compressors because these multiple dispersive elements must be identical and have identical incidence angles. A simple small variation in the input beam pointing direction is enough to introduce significant amounts of the various spatiotemporal distortions.

Consider the original four-prism pulse compressor (Fig. 1). If aligned correctly, the net result is just the addition of negative GDD to the pulse. However, unless the elements have precisely the same composition and apex angles and are positioned at precisely the same incidence angles, some residual angular dispersion, spatial chirp, and pulse-front tilt will occur in the output pulse [5]. While GDD tuning in a prism compressor can occur via simple prism translation or more complex variation in the prism separations, in grating or grism compressors, GDD adjustment requires the more complex variation in the separations between the first two and last two elements, which must be maintained as equal. Worse, in prism, grating and grism designs, wavelength tuning requires adjusting and maintaining identical incidence angles of all four components. As a result, four-element pulse compressors are prohibitively cumbersome devices to use in practice.

Compressors have generally been simplified to two components by placing a periscope after the second element and folding the beam back through the first two elements (see Fig. 2). This design halves both the complexity and the size of the device, but the difficulty of maintaining equal angles of the two dispersive elements and the inability to readily tune GDD in grating and grism designs remain problematic.

A recently introduced single-prism pulse compressor solved all of the alignment issues by reducing the number of dispersive elements to one and permitting easy GDD tuning by simple translation of a corner cube [6] (see Fig.

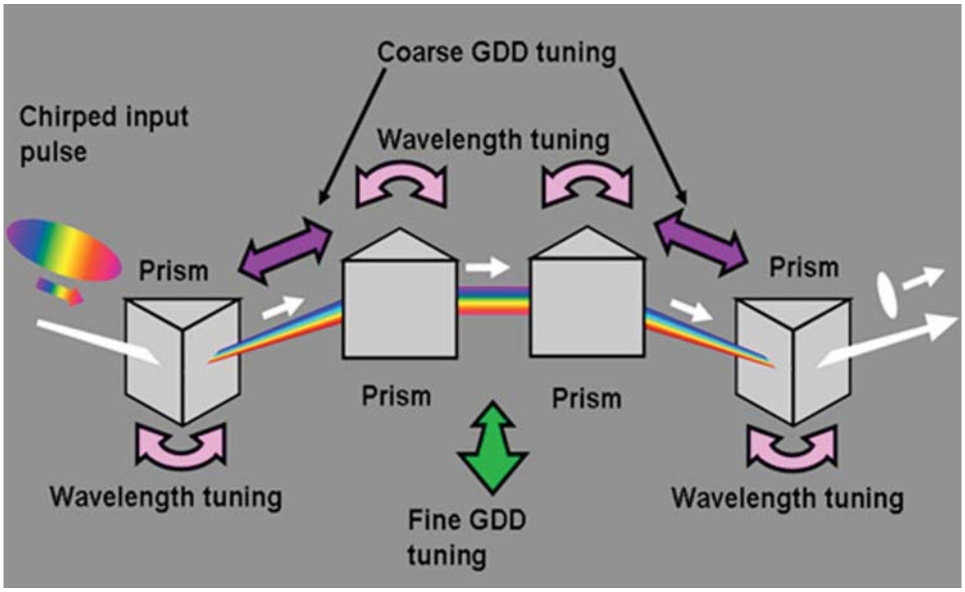

Fig. 1. (Color online) Conventional four-prism pulse compressor.

3). The beam *quadruple-passes* the prism, using the corner cube to retroreflect the beam back to the prism and simultaneously invert it (so the prism need not be inverted). Corner cubes are extremely accurately manufactured, so the dispersion added on the second (fourth) pass is equal and opposite to that in the first (third) pass. The device continues to use a (less critically aligned) roof mirror between the second and third passes through the prism (i.e., on the other side of it, as in two-prism compressors), where beam inversion is not appropriate and alignment is not as critical. Translating the corner cube varies the beam propagation distance between the prism passes and effectively tunes the GDD over a large range. Because the device tunes by varying the propagation distance between prism passes, it has the additional advantage that it can simultaneously accommodate both large and small bandwidths by simply changing the distance. This is a great advantage over two- and four-prism designs, which must use a fixed prism separation and which tune by moving a prism into and out of the beam, and so cannot accommodate large and small bandwidths unless significant additional realignment is performed.

Prism-based compressors, however, have limits on the magnitude of negative GDD that can be introduced. Since diffraction gratings and grisms are much more dispersive than prisms, grating and grism compressors can provide much larger amounts of negative GDD, approximately 2 orders of magnitude more than prism compressors for the same-size device.

So here we introduce single-grating and single-grism compressors based on this single-dispersive-component/corner-cube design. Single-grating (aberration-free) compressor designs [7] and devices based on the use of two roof mirrors have been introduced previously but do not achieve such alignment ease, and the use of corner cubes has not been mentioned in earlier work on grating or grism compressors, to the best of our knowledge. Usually, such compressors are used in chirped pulse amplification, where tuning of group-delay dispersion is not as important.

Our analysis of spatiotemporal distortions, however, shows that all previous grating and grism designs are

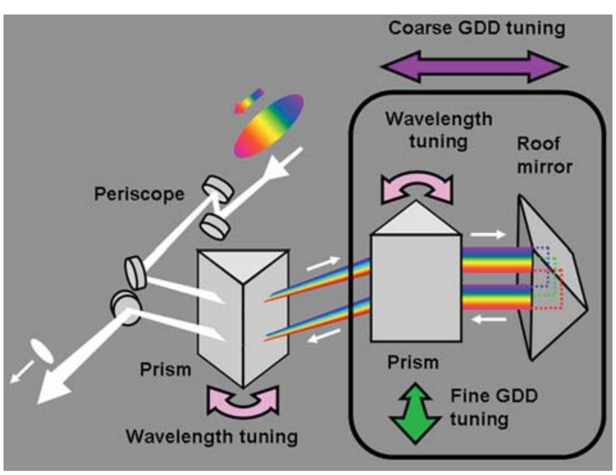

Fig. 2. (Color online) Two-prism pulse compressor.

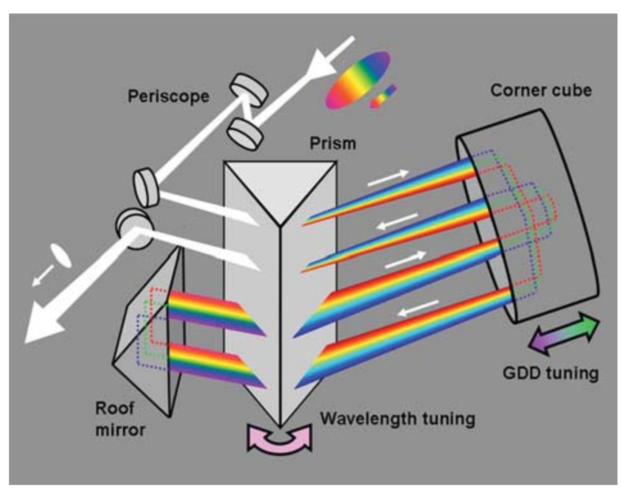

Fig. 3. (Color online) Schematic diagram of single-prism pulse compressor.

prone to them. After following careful alignment steps, such a compressor or stretcher is best left untouched, and input beam wander must be minimized. It is important to note that the magnitude of the undesired spatiotemporal distortions scales with the amount of GDD added by the compressor. Therefore, conventional compressor designs require even higher alignment precision when a highly dispersive element like a grating or a grism is used.

In our single-dispersive-element/corner-cube design, the use of the corner cube succeeds in achieving maximum accuracy for cancellation of all first-order spatiotemporal distortions, including angular dispersion, pulse-front tilt, and spatial chirp. In our design, tuning the GDD involves simply translating the corner cube, and tuning the wavelength involves simply tuning the grating angle. It also automatically achieves unity beam magnification. In addition, the corner cube causes the input beam to track the output beam; so, even if the compressor is bumped, it remains aligned. And due to the double-passing of the path, it is also half the size of analogous two-grating or two-grism devices. Finally, unlike current grating and grism designs, the same device can be used for a much larger bandwidth by simply restricting the corner cube distance.

As mentioned above, nearly all materials exhibit positive GDD (second-order dispersion) and also third-order dispersion (TOD) at wavelengths near 800 nm. It is well known that prism and grating compressors designed to compensate for a given amount of GDD cannot independently compensate for TOD. While materials nearly all have a positive TOD-to-GDD ratio, grating compressors always have a negative TOD-to-GDD ratio, so compensation of large amounts of GDD using a grating compressor actually exacerbates the TOD, thus yielding a highly distorted pulse in time. Prism-based compressors have the correct sign for this ratio but not the correct magnitude, and they lack ratio tuning and only offer a relatively small amount of GDD compensation. A grism [3,8] compressor of conventional design can address this issue, but current designs have the same limitations as conventional grating and prism designs because they consist of multiple dispersive elements and cannot be easily tuned for varying amounts of GDD. A single-grism pulse compressor, on the other hand, is automatically aligned for zero spatiotemporal distortions and can compensate for both GDD and TOD simultaneously.

In this work, we extend the single-dispersive-element compressor concept to grating and grism compressors. Both of these devices have all of the above advantages and, in addition, our single-grism pulse compressor compensates for material dispersion up to the third order. And using it, we demonstrated fourth-order limited-dispersion compensation for a 30 nm bandwidth, 800 nm wavelength pulse that had propagated through 10 m of optical fiber.

2. SINGLE-DISPERSIVE-ELEMENT PULSE COMPRESSORS

Our single-diffraction-grating pulse compressor uses only three elements: a reflection grating, a corner cube, and a roof mirror. The input beam diffracts off the reflection grating and impinges on to the corner cube, which retroreflects this angularly dispersed beam antiparallel to the one incident on it, with the spatial order of colors reversed (see Fig. 4). This inverts the beam on the second pass and causes a sign reversal of the angular dispersion introduced by the grating relative to that of the first pass. Therefore, after the first two passes, the angular dispersion in the beam is compensated, as required. A roof mirror reverses the beam path at a different height while maintaining the same order of colors in the dispersed beam. The last two passes thus remove both the spatial chirp and pulse front tilt while doubling the magnitude of GDD, as required.

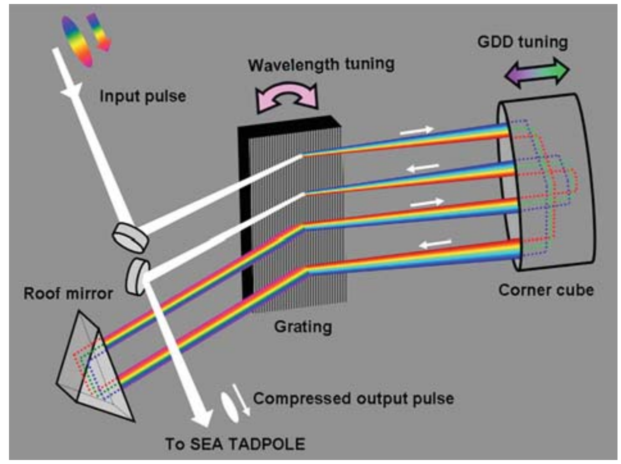

Fig. 4. (Color online) Schematic diagram of single-grating pulse compressor.

The single-grism design follows directly from the earlier single-prism compressor [5], and the single-grating design mentioned in the previous section. We replaced the grating in the single-dispersive-element design with a reflection grism as shown in Fig. 5. The grism used in this experiment is a right-angled SF2 glass prism with a 600 groove-per-mm reflection grating glued to its base. The input beam is incident on the face of the grism, which is orthogonal to the grating. It then undergoes total internal reflection at the diagonal face of the grism and finally exits the diagonal face of the grism after it diffracts off the grating. The beam path in each pass through the grism is

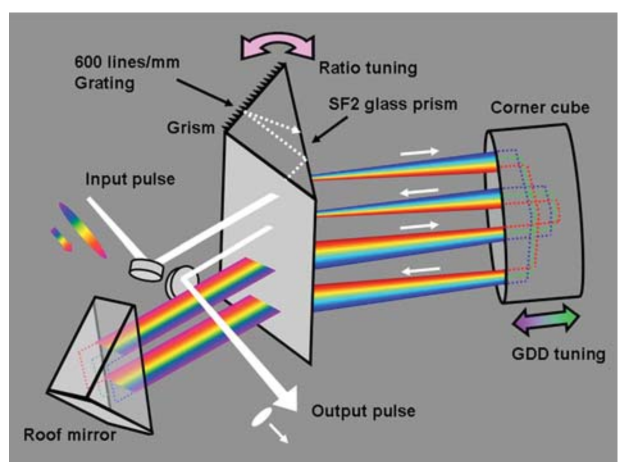

Fig. 5. (Color online) Schematic diagram for single-grism pulse compressor.

depicted on the top of the grism with a dashed line (see Fig. 5). After the first pass, the beam is reflected back onto the grism using a corner cube. As in the single-prism design [5], the corner cube functions as a retroreflector and a beam inverter, and the device functions analogously to the single-prism and single-grating designs. At the correct angle of incidence, however, the output pulse thus obtained has negative GDD *and* negative TOD in the correct ratio to cancel out material dispersion to the third order, and it has no spatiotemporal distortions.

3. MODELING AND SIMULATION

A. Single-Grating Pulse Compressor

1. Unity Beam Magnification

The corner cube very accurately retroreflects the beam, so the exit angle after the first pass is equal to the incidence angle for the second pass. An analytical calculation using Kostenbauder matrices [9] shows that the spatial magnification of the beam for each pass is:

$$M_1 = -\frac{\sin\varphi}{\sin\psi} = M_3 \quad \text{and} \quad M_2 = -\frac{\sin\psi}{\sin\varphi} = M_4, \qquad (1)$$

where φ and ψ are the diffracted and incidence angles of the beam measured from the grating surface (not the normal to it), the definitions of the angles in Kostenbauder's paper. Therefore, the total magnification of this device is always unity. The above calculation also applies to angular magnification.

2. Wavelength Tuning of the Single Grating Pulse Compressor

Once this device is set up to operate at a particular wavelength, it is easy to tune for other wavelengths. As is evident from the figure (see Fig. 4) shown above, looking from the top, the grating is rotated counterclockwise if wavelength is decreased and clockwise for longer wavelengths. The beam path in the device does not change in either case. Therefore, this device can be tuned for a different wavelength by rotating just one knob, which rotates the only grating used.

3. No Spatiotemporal Distortions

Again, using the Kostenbauder matrix formalism, it is easily deduced that the beam emerging from the single-grating compressor has zero pulse-front tilt, zero spatial chirp, and zero residual angular dispersion. Since, as mentioned, the corner cube retroreflects the beam, the exit angle after the first pass is the same as the incidence angle for the second pass. Therefore, the compressor is auto-aligned to introduce zero distortions, independent of the incidence angle of the beam.

$$K = K_{\text{grating}} K_{\text{space}} K_{\text{grating}} K_{\text{mirror}} K_{\text{grating}} K_{\text{space}} K_{\text{grating}} . \qquad (2)$$

The calculated Kostenbauder matrix [Eq. (2)] shows that added spatial chirp $K_{1,4}$, angular dispersion $K_{2,4}$, and pulse front tilt $K_{1,3}$ are all zero. The GDD, $K_{3,4}$, is negative, as required.

4. Negative Group-Delay Dispersion

The analytical result for GDD using the Kostenbauder matrix formalism is exactly the same as that obtained by differentiating the phase introduced by a grating compressor [Eq. (3)].

$$GDD_{\text{grating}} = -\frac{\lambda^3}{2\pi c^2}\frac{b}{d^2\cos^2\theta}\bigg|_{\lambda_0}, \qquad (3)$$

where θ is diffraction angle measured from the grating normal, b is the path length inside the compressor, and the grating groove spacing is d.

B. Single-Grism Pulse Compressor

We also used Kostenbauder matrices to model the single-grism pulse compressor. The matrix for each pass through the grism can be obtained by treating it as a composite optical element composed of a tilted air-glass interface, a reflection grating, and another tilted glass-air interface. Using the matrix for each grism pass, the Kostenbauder matrix for the compressor is given as

$$K_c = K_{\text{grism}} K_{\text{space}} K_{\text{grism}} K_{\text{mirror}} K_{\text{grism}} K_{\text{space}} K_{\text{grism}} . \qquad (4)$$

The elements of the calculated matrix [Eq. (4)] that correspond to spatiotemporal distortions are found to be all zero. The calculated Kostenbauder matrix shows that the spatial magnification $K_{c\ 1,1}$ and angular magnification $K_{c\ 2,2}$ are unity. Spatial chirp $K_{c\ 1,4}$, angular dispersion $K_{c\ 2,4}$, and pulse front tilt $K_{c\ 1,3}$ are all zero. And again, GDD $K_{c\ 3,4}$ is negative, as required. This shows that there is fundamentally no spatial chirp, residual angular dispersion, or pulse front tilt in the output of this device. Since the pulse travels equal distances inside the corner cube, the spatial chirp introduced in the first two passes is completely removed in the last two passes in the compressor. Therefore, there is no mismatch in the angle of incidence for the first two and last two passes of the pulse through the grism. This ensures that the angular dispersion is completely cancelled in the compressor.

4. EXPERIMENT

A. Group Delay Dispersion

In our experiments, a transform-limited pulse from a KM Labs Ti:sapphire oscillator centered at 825 nm with a FWHM bandwidth of 30 nm was stretched using the single-grating pulse compressor. The corner cube consists of silver coated mirrors and has an angular tolerance of 3 arc seconds. The angle of incidence of the input beam is 62 degrees from the grating normal and the grating has a groove density of 600 lines/mm. The phase introduced by the compressor was measured using spatially encoded arrangement for temporal analysis by dispersing pair of light E-fields (SEA TADPOLE) [10,11] and a polynomial fit returned the GDD for varying separation of the corner cube and the grating (Fig. 6). The measured values of GDD were then plotted with the corner cube separation. The variation was found linear and in very good agreement with the simulations from the previous section.

Similarly, the dispersion introduced into the output pulse by the single-grism pulse compressor was also measured using SEA TADPOLE. The input pulse was cen-

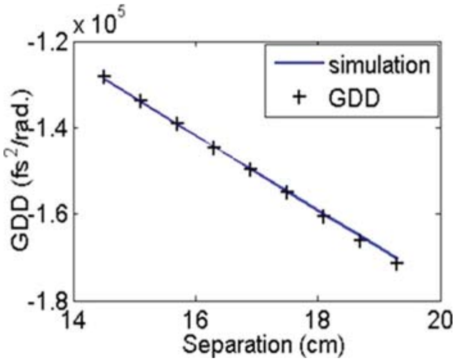

Fig. 6. (Color online) Variation of GDD versus distance in single-grating pulse compressor.

tered at 800 nm with a bandwidth of 30 nm. The incidence angle was fixed at 8.4 degrees from the grism surface normal. The GDD introduced by the compressor at each grism-corner cube separation is plotted below (see Fig. 7).

B. Measurement of Spatiotemporal Distortions

1. Spatial Chirp

The spatial chirp in the output pulse from the single-grating compressor and the single-grism compressor was measured experimentally using an imaging spectrometer [12]. The beam to be examined was dispersed in the direction of one of the beam's spatial coordinates, which was orthogonal to the one in which the beam was expected to have some spatial chirp, i.e., the dimension in which angular dispersion is introduced by the grating or the grism. The spatiospectral plot below shows that there was no measurable spatial chirp in the output beam from the single grating pulse compressor. The spatial-chirp rho parameter [13] calculated from the spatiospectral plot shown (Fig. 8) gave a value of 0.05, which is at the detection limit of our device. We obtained the same result for the single-grism pulse compressor.

2. Angular Dispersion and Pulse-Front Tilt

The two compressors do not introduce any pulse-front tilt or residual angular dispersion in the beam. It can be shown easily that residual angular dispersion, if present in the beam, will cause some spatial chirp to occur after propagating some distance after the compressor. Therefore, for measuring angular dispersion, a good check is to measure the spatial chirp at two different locations along the beam path after the beam exits the pulse compressor. Our measurements confirmed that there was no residual angular dispersion introduced by the two compressors. Because there are only two independent (and six dependent) first-order spatiotemporal distortions, the absence of two of them simultaneously, that is, angular dispersion and spatial chirp, guarantees that there is no pulse-front tilt in the beam either. Therefore, there are no (first-order) spatiotemporal distortions introduced by the single grating and the single grism pulse compressors.

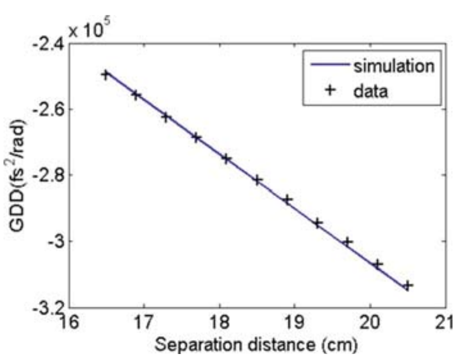

Fig. 7. (Color online) GDD versus distance in single-grism pulse compressor.

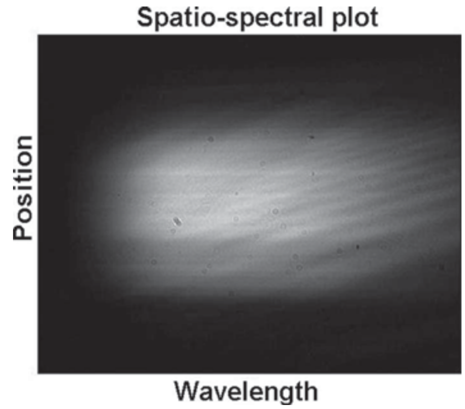

Fig. 8. Spatiospectral plot revealing the lack of spatial chirp in the compressor output after four beam passes, indicated by the lack of tilt in this plot. The minor structure and the fringes at right are due to a stray reflection also entering the spectrometer and hence are of no significance.

C. Third-Order-Dispersion Compensation

To demonstrate third-order-dispersion compensation, a pulse from a Ti:sapphire oscillator at a center wavelength of 805 nm was stretched using a 10 m long optical fiber. The input pulse incident on the fiber had a FWHM pulse width of 90 fs and a spectral bandwidth of 30 nm as measured by a Swamp Optics GRENOUILLE. The spectral phase of the pulse after the fiber and before the compressor was also measured using SEA TADPOLE (see Fig. 9).

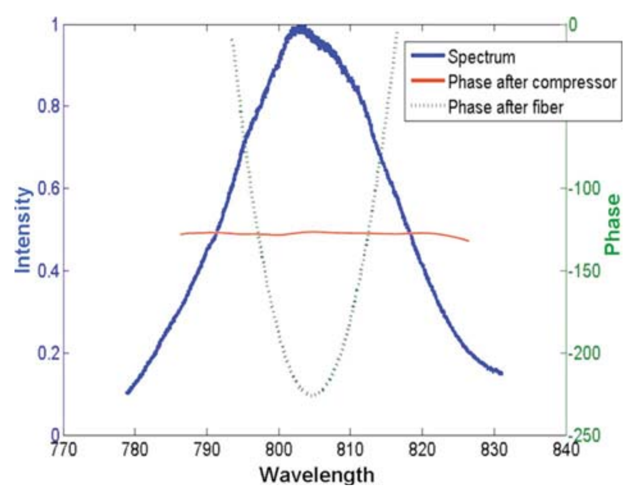

Fig. 9. (Color online) Spectrum and spectral phase before and after the compressor.

A fiber collimator attached to the end of this fused silica optical fiber collimated the beam, which then served as the input to the single-grism pulse compressor. The collimated beam was incident upon the grism at an angle of 8° from the grism surface normal. The curvature of the phase being monitored using SEA TADPOLE decreased as the corner cube was translated further from the grism. After removing the second-order phase, minor adjustments in the incidence angle and corner-cube position yielded an almost flat-phase output pulse. The measured spectrum and the spectral phase of the output are shown below (Fig. 9). The spectral phase of the output pulse shows that the dispersion introduced by the optical fiber was completely removed up to and including the third order. Additionally, the compressor works for both horizontal and vertical polarizations. Neither the metal corner cube nor the roof mirror rotates the polarization of the beam, so the output beam maintains the same polarization as the input. However, gratings and grisms have different diffraction efficiencies for the two orthogonal polarizations, so use of an intermediate polarization would yield some polarization rotation.

5. CONCLUSIONS

We have demonstrated single-dispersive-element compressors using a grating and a grism. They are easily aligned, automatically distortion free, one-fourth or half the size of previous equivalent compressors, and they can easily be tuned for the operating wavelength and varying amounts of GDD, and, with the grism device, for GDD-to-TOD ratio. The use of a grating as the dispersive element improves the ability to compensate for GDD by more than an order of magnitude compared to any prism compressor [5], while the single-grism pulse compressor should be of great utility when compensation for large amounts of material dispersion up to and including the third order becomes necessary, for example, in fiber delivery of ultrashort pulses.

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