Distortion-Free Single-Prism/Grating Ultrashort Laser Pulse Compressor

Vikrant K. Chauhan, Jacob Cohen, Peter M. Vaughan, Pamela Bowlan, and Rick Trebino

***Abstract*— We introduce an ultrashort laser pulse compressor that uses a single-prism and a single-grating. It is compact and automatically aligned and compensates for significant second- and third-order material dispersion. This design inherently 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 common to pulse compressors. It is comprised of only four elements: a prism, a diffraction grating, a corner cube, and a roof mirror. It can provide large amounts of negative group-delay dispersion with small translations of the corner cube. Unlike conventional compressors, the device can operate on pulses with both large and small bandwidths by varying the corner cube position. Using this compressor, we demonstrate compensation of 12 m of optical fiber for 800-nm pulses with 30 nm of bandwidth.**

***Index Terms*— Chirping, pulse compressors, ultrafast devices.**

I. Introduction

DUE to their large bandwidths, ultrashort laser pulses are prone to numerous distortions, which can be spatial, temporal, or spatiotemporal in nature. Group-delay dispersion (GDD) is a temporal distortion, in which longer wavelengths propagate faster than shorter ones in the visible and near-IR, lengthening the pulse in time and reducing its peak intensity. It is therefore important to compensate for GDD in most applications of ultrashort pulses, such as imaging and micromachining. Pulse compressors, using prisms or gratings as dispersive elements, can compensate for this effect because angular dispersion always yields negative GDD [1]–[3]. Unfortunately, introducing angular dispersion into a pulse also introduces other spatiotemporal distortions [4], such as pulse-front tilt and spatial chirp, which, along with the angular dispersion itself, must all be compensated before using the pulse. As a result, pulse compressors have two or four identical dispersive elements, arranged, not only to introduce negative GDD, but also to then compensate for these additional spatiotemporal distortions (Fig. 1).

This latter requirement entails the use of identical dispersive elements, operated at identical angles and identical separations. The traditional designs for pulse compressors are thus bulky and difficult to align for distortion-free output. For example, even in a two-prism pulse compressor (which double-passes a prism pair as shown in Fig. 2), the two prisms must be identical and have identical incidence angles, or the output pulse will have residual angular dispersion, spatial chirp, and pulse-front tilt.

We recently introduced a *single-prism* pulse compressor that solved all of these problems for pulses with small to moderate amounts of chirp [5]. After the first and third passes through the prism, a precisely manufactured corner cube retroreflects and inverts the beam, obviating the need for additional prisms, and all these undesired distortions precisely cancel out (see Fig. 3). But prism compressors have limited negative GDD, and the commonly occurring cases of massive GDD require more negative GDD. Use of a grating as the dispersive element provides up to 100 times more negative GDD for the same size compressor [6], [7]. So we extended the idea to single-grating compressors [8], [9]. However, gratings have a negative ratio of third-order dispersion (TOD) to GDD, whereas all materials introduce a positive ratio, so this device, like other grating compressors, can exacerbate TOD.

A prism compressor in conjunction with a grating compressor has been shown to be able to compensate for higher order dispersion, but such a complex apparatus is extremely difficult to align and maintain aligned [3], so this approach is rarely used. Another proposed solution [10] to this problem uses off-axis and/or tilted lenses within a prism or grating compressor. Unfortunately, the required lateral displacement and tilting of the lenses, which are important for tuning the higher order dispersion in this design, can cause serious spatial aberrations and distort the beam's spatial profile. Use of a grism (a grating written on a prism) as the dispersive element achieves a variable ratio of third- to second-order dispersion and so can solve this problem [11]–[13]. So, we have also extended our single-dispersive-element design to include a grism compressor [8], [9]. But grisms are expensive, and the choice is restricted to only a very small number of commercially available parameters, which usually do not suit the requirements of the relevant experiments.

II. Single-Prism/Grating Pulse Compressor

Obviously, one could, in principle, simulate a grism using a grating and prism combination and implement a prism/grating combination compressor using two or four identical prism/grating combinations in a manner analogous to the grism compressor. However, this approach would be extremely

Manuscript received May 14, 2010; revised July 16, 2010; accepted July 25, 2010. Date of current version October 6, 2010.

The authors are with the School of Physics, Georgia Institute of Technology, Atlanta, GA 30332 USA (e-mail: vikrant@gatech.edu; jcohen7@gatech.edu; PeterMVaughan@gatech.edu; pambowlan@gmail.com; rick.trebino@physics.gatech.edu).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JQE.2010.2063017

0018–9197/$26.00 © 2010 IEEE

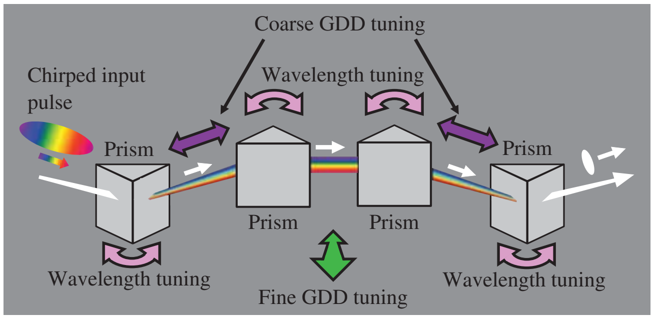

Fig. 1. Original four-prism pulse compressor.

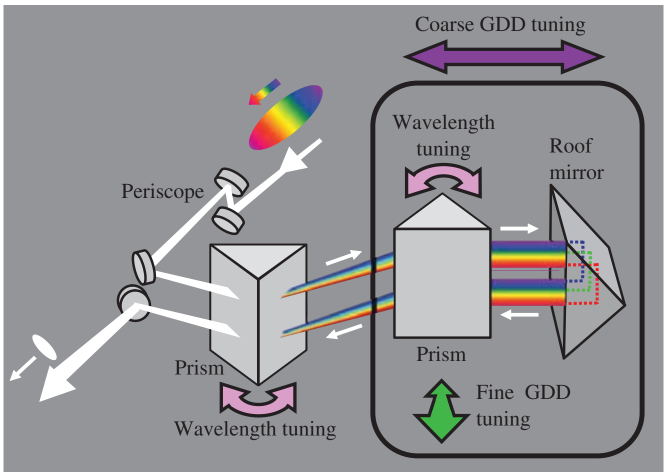

Fig. 2. Two-prism pulse compressor.

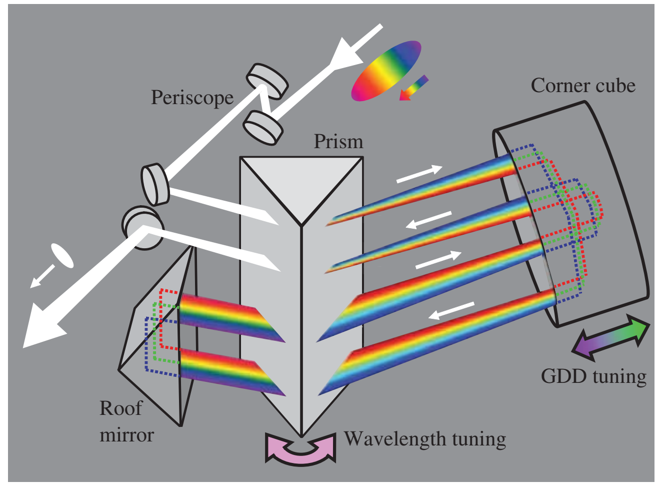

Fig. 3. Single-prism pulse compressor.

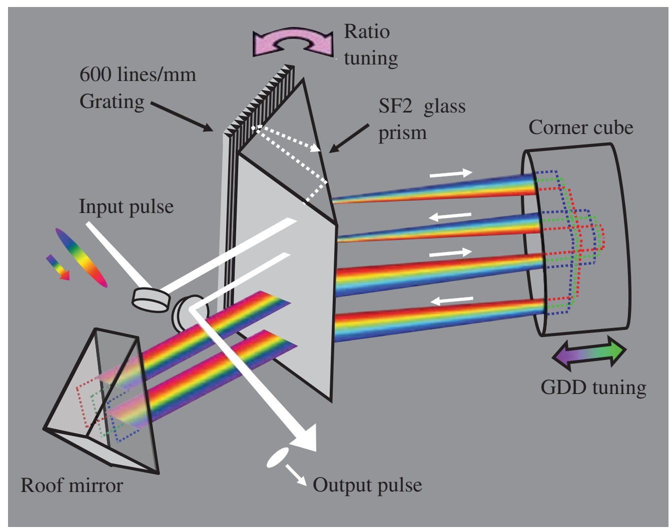

Fig. 4. Single-prism/grating pulse compressor.

difficult to align, so, despite its obviousness, it has not been reported or even attempted, to our knowledge. It becomes much easier to implement such an approach using the idea of a single-dispersive-element, yielding a pulse compressor that uses a single-prism/grating combination. In our device, the prism and the grating are mounted together and they have a fixed relative separation and orientation. For GDD tuning, only the corner cube needs to be translated, and for ratio tuning the incidence angle of the input beam is varied. Indeed, it is quite easy to set up and align our single-dispersive-element compressor containing only one grating and one prism.

A compressor using two prism/grating combinations has eight translational and four rotational degrees of freedom for alignment. The angular dispersion introduced by a prism/grating combination is generally more than just the sum of the individual dispersions added by each [see (3)]. In compressors that use highly dispersive devices, a slight misalignment introduces large distortions. A simple calculation shows that 1° of angular mismatch in a grating pair compressor that uses a pair of 1200 lines/mm gratings causes a large angular dispersion (∼0.9) in the pulse at the output, and on propagating a few meters, significant spatial chirp (∼0.5) and pulse-front tilt (∼0.5) occur. The value for each distortion was calculated in terms of normalized parameters introduced in [14]. In order to tune GDD and the TOD to GDD ratio, the prisms and the gratings have to be rotated and translated while maintaining the alignment, which is nearly impossible to achieve in practice.

Our design uses a roof mirror, a corner cube, a grating, and a dispersive prism. In our design, the beam passes four times both the dispersive elements and, like our previous single-dispersive-element designs, is automatically aligned for distortion-free output. It provides significantly more GDD than a prism compressor and, unlike a grating compressor, can tune the TOD to GDD ratio introduced. Additionally, this design allows the use of all available gratings and prisms, and thereby opens up the concept to an even wider range of applications. In our compressor, the tuning of GDD and the TOD to GDD ratio is remarkably easy, so it can compensate for material dispersion up to (and including) third-order for a wide range of materials.

Fig. 4 shows a schematic diagram of an implementation of the device that we built. The dashed line (shown on the top) shows the beam path as it undergoes total internal reflection at the oblique face of the prism and then exits from the face parallel to the reflection grating, kept at a distance of ∼5 mm from the prism. The first-order diffracted beam from the grating enters the prism again from the same face and

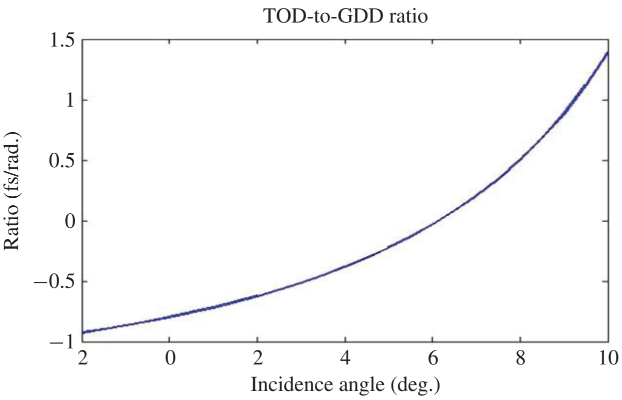

Fig. 5. Ratio variation with the incidence angle calculated using ray tracing.

finally exits from the oblique face. The beam is vertically displaced and reflected back in the same direction using a corner cube, which also reverses the spatial order of colors and inverts the beam for the second pass. Thus, as in other dispersive compressors, angular dispersion is removed after the first two passes, at which point the beam only has spatial chirp, negative GDD, and some pulse-front tilt. It is then reflected back onto the prism at a different height using a roof mirror for the final two passes to cancel out the spatial chirp and pulse-front tilt. The net effect is the addition of negative GDD and TOD, depending on the corner cube position and the incidence angle of the beam.

We also performed numerical simulations of the single-prism/grating compressor in MATLAB using the Kostenbauder-matrix formalism [15] and ray tracing.

III. General Characteristics of the Compressor Design

The GDD is mainly determined by the prism/grating combination and path between the first and second passes as in other grating compressors. Tuning of the TOD to GDD ratio is easily achieved by changing the incidence angle of the beam into the prism/grating combination or, equivalently, into the device as a whole. Using ray tracing, we calculated the angle of incidence for the correct TOD to GDD ratio. Its value depends on the prism shape, the prism material, and the grating used. Once the beam is aligned into the compressor at the correct angle, the prism/grating combination can then be rotated to fine-tune the ratio to the desired value. In our simulation, we found that, with a variation of less than 4° in the input incidence angle, the ratio can be tuned from 0 to 1 fs/rad (Fig. 5).

At 800 nm, most materials introduce a ratio of 0.75 fs/rad. So our compressor can compensate for dispersion up to third-order for essentially all materials.

A. Beam Magnification

Prisms have unity magnification at Brewster's angle incidence, designed to be the incidence angle for minimum deviation (i.e., when the input and output angles are equal). This is almost never, in fact, the case for any pulse compressor, as this condition is only met at one wavelength. Additionally, for the TOD to GDD ratio tuning, the angle of incidence must be tuned in the device. Therefore, on the first pass through the prism/grating pair, the beam experiences 1-D spatial magnification. However, on the second pass through the two dispersive elements, the beam is reflected back from the corner cube and all the output angles now become the input angles, so it experiences a demagnification by the same amount. Therefore, the overall beam magnification introduced by this compressor is unity as

$$M_1 = \frac{1}{M_2} = M_3 = \frac{1}{M_4}. \tag{1}$$

This result holds for all gratings and prisms. This is confirmed from the Kostenbauder matrix for this compressor, as the matrix elements corresponding to the spatial and angular magnification are both unity.

B. Spatiotemporal Distortions

Propagation of a beam with angular dispersion increases not only the beam spot size in the transverse dimension of the angular dispersion but also the pulse width significantly over a distance of a few meters and generates a large spatial chirp. Even a small misalignment in a compressor that uses a highly dispersive element, such as a grating, can distort the output pulse significantly. However, it is important that the output angular dispersion remain zero as the GDD and/or the TOD to GDD ratio is tuned. Because translating the corner cube to vary the GDD will not affect any device angles, it need not be considered, if the dispersion is zero for one value of GDD, it will be for them all. But we must verify that the variation of the incidence angle with ratio tuning does not cause the output angular dispersion to be nonzero, as it easily can in current pulse compressors. The angular dispersion introduced by a prism/grating pair depends on which direction the beam propagates through it. Each pass through the prism/grating pair can be divided into three parts as the pulse goes through the prism (referred to as prism 1 in this section), the grating, and then the prism again (referred to as prism 2 in this section). The magnification M on each pass is just the product of the three individual magnifications

$$M = M_{prism1} M_{grating} M_{prism2}. \tag{2}$$

Let D be the dispersion introduced by a device. The dispersion introduced in the first pass through the prism/grating pair is given by a simple result [16], [17] that gives the total dispersion of an arbitrary sequence of dispersive devices in terms of only their dispersions and magnifications. The total dispersion is the sum of the individual dispersions, each divided by the total magnification as follows:

$$D = \frac{D_{prism1}}{M_{grating} M_{prism2}} + \frac{D_{grating}}{M_{prism2}} + D_{prism2}. \tag{3}$$

It is easy to show that, if a prism/grating pair has dispersion D and magnification M in the forward direction, it has dispersion MD in the reverse direction. Thus, after accounting for the beam inversion by the corner cube, the angular dispersion added on each pass through the prism/grating pair is

$$MD_1 = -D_2 = -MD_3 = D_4. \tag{4}$$

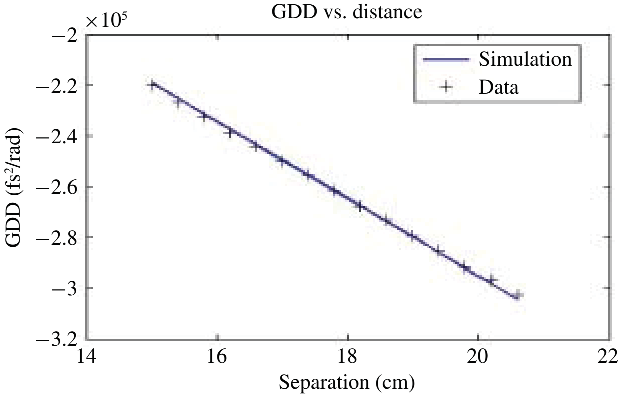

Fig. 6. GDD variation with corner cube separation.

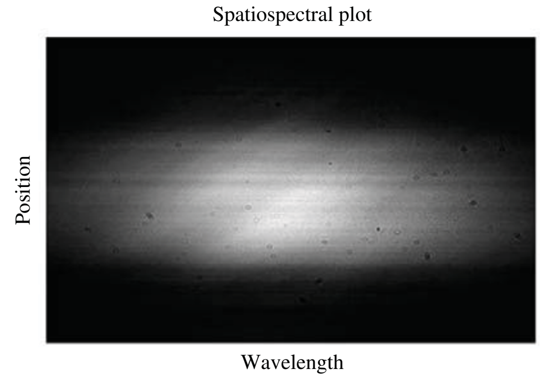

Fig. 7. Spatiospectral plot of the output pulse.

To calculate the total dispersion added by the compressor, we again use the same result as in (3), but this time for a sequence of prism/grating pairs as they are visited by the pulse on each pass

$$D_{tot} = \frac{D_1}{M_2 M_3 M_4} + \frac{D_2}{M_3 M_4} + \frac{D_3}{M_4} + D_4. \qquad (5)$$

Substituting values from (1) and (4), it is seen that the total angular dispersion added by the device is precisely zero for all angles of incidence. Additionally, on constructing the Kostenbauder matrix for this compressor, it is easily seen that the angular dispersion, spatial chirp, and pulse-front tilt introduced by this compressor are all zero for all possible prisms and gratings.

C. Other Considerations

Additionally, like other dispersive compressors, this design 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 prisms have different diffraction efficiencies for the two orthogonal polarizations, so use of an intermediate polarization would yield some polarization rotation.

IV. Experiment

Our prism was composed of SF2 glass and had an apex angle of 90° and an input face 5 cm × 5 cm. The beam angle of incidence on the prism was 8° from the prism normal. The beam underwent the total internal reflection shown in Fig. 4, but this does not change the device properties, and it generated a conveniently located output beam. Our 5-cm-long grating was reflective and had 600 lines/mm. The beam incidence angle on the grating was 8° and the (first-order) diffracted beam emerged at 20° from the grating normal. The prism and the grating were mounted together on a rotation stage, and the grating was kept parallel to the prism at a distance of about 5 mm (this value was chosen for experimental convenience and does not alter the TOD to GDD ratio). The corner cube consisted of silver-coated mirrors and had an angular tolerance of 3 arc-seconds. Its diameter was 63.5 mm. It was placed after the prism/grating combination to reflect the diffracted beam back toward it, as in Fig. 4.

Transform-limited pulses from a KM Laboratories Ti:sapphire oscillator, centered at 805 nm with a full-width-at-half-maximum (FWHM) bandwidth of 30 nm, were stretched (by down-chirping) using our pulse compressor. We measured the phase introduced by the compressor using SEA TADPOLE and a polynomial fit returned the GDD introduced at each position of the corner cube. The GDD values thus obtained were plotted with the corner cube separation, as shown in Fig. 6. The variation was found linear and in very good agreement with the theory.

In order to verify the lack of spatiotemporal distortions, we examined the output beam by looking at the spatiospectral plot $I(x, \omega)$ at the output of a spectrometer. Any noticeable tilt in this 2-D plot would be indicative of some spatial chirp [18] in the output, but no tilt was observed in the plot (see Fig. 7). Using this plot, we calculated a dimensionless parameter ρ, which is a very sensitive measure for spatial chirp at small values [14]. The spatial chirp measured was <0.02, which is at the detection limit of our measurement.

To measure the residual angular dispersion, a lens was introduced in the output beam to map angles to position at the slit of an imaging spectrometer. A similar plot was obtained for $I(k_x, \omega)$, and the ρ-value for angular dispersion was also at the detection limit. In the absence of spatial chirp and angular dispersion, pulse-front tilt is also necessarily absent in a beam. We conclude that, as predicted, there were no spatiotemporal distortions in the output beam.

In order to demonstrate TOD compensation, a pulse from a Ti:sapphire oscillator at a center wavelength of 805 nm was stretched using a 12-m-long optical fiber. The somewhat chirped input pulse coupled into the fiber had an FWHM pulse width of 90 fs and a spectral bandwidth of 30 nm, as measured by a Swamp Optics GRENOUILLE [19]. The input pulse chirp does not interfere with our measurements. Using SEA TADPOLE [20], we measured the phase difference between the stretched pulse after the fiber and the input pulse which is used as the reference. This tells us the spectral phase added by the optical fiber alone (see Fig. 8). After the fiber, the beam was collimated by a fiber collimator and sent into the compressor. The second-order spectral phase of

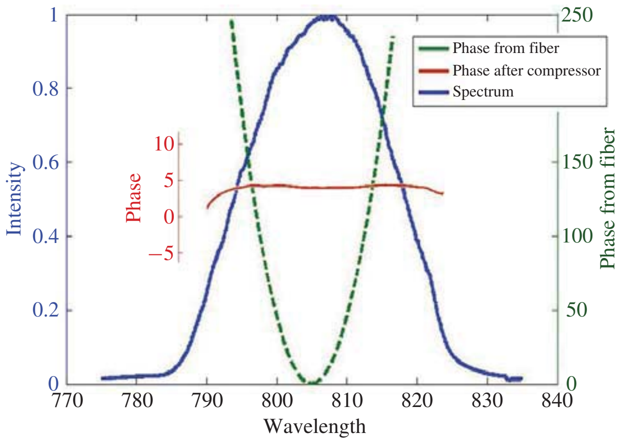

Fig. 8. Spectrum of the pulse after going through the fiber and the compressor. The spectral phase shown in green is the phase added to the pulse by 12 m of fused silica fiber. The pulse after the fiber goes through the compressor which compensates for almost all of the GDD and TOD that was added by the fiber. The phase shown in red is the phase of the final output pulse, after both the compressor and the fiber, with reference to the input pulse.

the output pulse after the compressor was monitored using SEA TADPOLE [20] and decreased as the corner cube was translated further from the grating/prism combination. After removing the second-order phase, minor adjustments in the incidence angle and corner cube position yielded an almost flat phase (see Fig. 8). The spectral phase of the output pulse shows that the dispersion introduced by the optical fiber was completely removed up to and including third-order. The residual phase is mostly quartic as is evident from Fig. 8.

V. Discussion

Because only one set of dispersive components needs to be aligned in this device, one need not stop at the use of two components in this design. As a result, it paves the way for even higher order dispersion compensation by adding as many dispersive elements (of any kind and at any angle) as one chooses without a significant increase in complexity. And because the achievable GDD scales as the square of the total dispersion, one could increase the achievable GDD by a large factor by simply adding more easily aligned dispersive elements.

VI. Conclusion

In conclusion, we have developed a simple, elegant, and versatile pulse compressor that has all the benefits of a single-grism pulse compressor. It adds significantly more negative GDD than a prism-based compressor and compensates for TOD as well—but avoids the need for difficult-to-obtain grisms. Our design is very easy to tune for TOD to GDD ratio and dispersion, and it is very compact—about a fourth or a half the size of previous designs. It automatically yields zero angular dispersion, zero spatial dispersion, zero pulse-front tilt, and unity magnification. It should be useful for many purposes, including pre-compensating for fiber-induced chirp, so that one Ti:sapphire laser could supply transform-limited pulses through equal-length fibers to multiple experimental setups in many different rooms.

References

[1] O. E. Martinez, J. P. Gordon, and R. L. Fork, "Negative group-velocity dispersion using refraction," *J. Opt. Soc. Am. A*, vol. 1, no. 10, pp. 1003–1006, 1984.
[2] W. Dietel, J. J. Fontaine, and J. C. Diels, "Intracavity pulse compression with glass: A new method of generating pulses shorter than 60 fsec," *Opt. Lett.*, vol. 8, no. 1, pp. 4–6, 1983.
[3] R. L. Fork, C. H. B. Cruz, P. C. Becker, and C. V. Shank, "Compression of optical pulses to six femtoseconds by using cubic phase compensation," *Opt. Lett.*, vol. 12, no. 7, pp. 483–485, 1987.
[4] S. Akturk, X. Gu, P. Gabolde, and R. Trebino, "The general theory of first-order spatio-temporal distortions of Gaussian pulses and beams," *Opt. Exp.*, vol. 13, no. 21, pp. 8642–8661, 2005.
[5] S. Akturk, X. Gu, M. Kimmel, and R. Trebino, "Extremely simple single-prism ultrashort-pulse compressor," *Opt. Exp.*, vol. 14, no. 21, pp. 10101–10108, 2006.
[6] G. Cheriaux, P. Rousseau, F. Salin, J. P. Chambaret, B. Walker, and L. F. Dimauro, "Aberration-free stretcher design for ultrashort-pulse amplification," *Opt. Lett.*, vol. 21, no. 6, pp. 414–416, 1996.
[7] M. Lai, S. T. Lai, and C. Swinger, "Single-grating laser pulse stretcher and compressor," *Appl. Opt.*, vol. 33, no. 30, pp. 6985–6987, 1994.
[8] V. Chauhan, P. Bowlan, J. Cohen, and R. Trebino, "Single-grating and single-grism pulse compressors," in *Proc. CLEO/Int. Quantum Electron. Conf., OSA Tech. Dig.*, 2009, no. CMLL7, pp. 1–3.
[9] V. Chauhan, P. Bowlan, J. Cohen, and R. Trebino, "Single-diffraction-grating and grism pulse compressors," *J. Opt. Soc. Am. B*, vol. 27, no. 4, pp. 619–624, 2010.
[10] W. E. White, F. G. Patterson, R. L. Combs, D. F. Price, and R. L. Shepherd, "Compensation of higher-order frequency-dependent phase terms in chirped-pulse amplification systems," *Opt. Lett.*, vol. 18, no. 16, pp. 1343–1345, 1993.
[11] S. Kane and J. Squier, "Grism-pair stretcher compressor system for simultaneous second- and third-order dispersion compensation in chirped-pulse amplification," *J. Opt. Soc. Am. B*, vol. 14, no. 3, pp. 661–665, 1997.
[12] E. A. Gibson, D. M. Gaudiosi, H. C. Kapteyn, R. Jimenez, S. Kane, R. Huff, and C. G. Durfee, "Efficient reflection grisms for pulse compression and dispersion compensation of femtosecond pulses," *Opt. Lett.*, vol. 31, no. 33, pp. 3363–3365, 2006.
[13] S. Kane, J. Squier, J. V. Rudd, and G. Mourou, "Hybrid grating-prism stretcher-compressor system with cubic phase and wavelength tunability and decreased alignment sensitivity," *Opt. Lett.*, vol. 19, no. 22, pp. 1876–1878, 1994.
[14] P. Gabolde, D. Lee, S. Akturk, and R. Trebino, "Describing first-order spatio-temporal distortions in ultrashort pulses using normalized parameters," *Opt. Exp.*, vol. 15, no. 1, pp. 242–251, 2007.
[15] A. G. Kostenbauder, "Ray-pulse matrices: A rational treatment for dispersive optical systems," *IEEE J. Quantum Electron.*, vol. 26, no. 6, pp. 1148–1157, Jun. 1990.
[16] V. Chauhan, J. Cohen, and R. Trebino, "Dispersion law for an arbitrary sequence of dispersive devices," *Appl. Opt.*, to be published.
[17] R. Trebino, "Achromatic N-prism beam expanders: Optimal configurations," *Appl. Opt.*, vol. 24, no. 8, p. 1130, 1985.
[18] X. Gu, S. Akturk, and R. Trebino, "Spatial chirp in ultrafast optics," *Opt. Commun.*, vol. 242, nos. 4–6, pp. 599–604, 2004.
[19] S. Akturk, M. Kimmel, P. O'Shea, and R. Trebino, "Extremely simple device for measuring 20-fs pulses," *Opt. Lett.*, vol. 29, no. 9, pp. 1025–1027, 2004.
[20] P. Bowlan, P. Gabolde, A. Schreenath, K. McGresham, and R. Trebino, "Crossed-beam spectral interferometry: A simple, high-spectral-resolution method for completely characterizing complex ultrashort pulses in real time," *Opt. Exp.*, vol. 14, no. 24, pp. 11892–11900, 2006.

Vikrant Chauhan received the integrated M.Sc. (5-year integrated B.Sc. and M.Sc.) degree in physics from the Indian Institute of Technology, Kharagpur, India, in 2006. Currently he is pursuing the Ph.D. degree in the School of Physics, Georgia Institute of Technology, Atlanta.

His current research interests include ultrafast optics, pulse compression, laser design, and ultrashort pulse measurement.

Jacob Cohen received the B.S. degree in physics from the University of Texas, Austin, in 2002, and the M.S. degree in applied physics from the University of Maryland, Baltimore. He is currently pursuing the Ph.D. degree in the School of Physics, Georgia Institute of Technology, Atlanta, under Prof. R. Trebino.

Pamela Bowlan received the Ph.D. degree in physics from Prof. R. Trebino's Group at Georgia Institute of Technology, Atlanta, in 2009.

She was previously a Swamp Optics Research Fellow and worked to extend the frequency resolved optical gating technique to measure nanosecond pulses. She is currently with the School of Physics, Georgia Institute of Technology, and from 2010 will begin a Post-Doctoral Fellowship at the Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy in Thomas Elsaesser's Group, Berlin, Germany. Her current research interests include the characterization of ultrashort pulses that are complex in time and/or space such as focused pulses or shaped pulses.

Peter Vaughan is pursuing the Ph.D. degree under Prof. R. Trebino at the Department of Physics, Georgia Institute of Technology, Atlanta.

His current research interests include the use of optical parametric amplification to imaging technology.

Rick Trebino was born in Boston, MA, on January 18, 1954. He received the B.A. degree from Harvard University, Cambridge, MA, in 1977, and the Ph.D. degree from Stanford University, Palo Alto, CA, in 1983.

He worked as a physical sciences Research Associate at Stanford University during a three-year term. He is currently with the School of Physics, Georgia Institute of Technology, Atlanta. His current research interests include the development of a technique for the measurement of ultrafast events in the frequency domain using long-pulse lasers by creating moving gratings.