

Extremely simple single-prism ultrashort-pulse compressor

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Abstract: We have designed and demonstrated a very simple and compact ultrashort-pulse compressor using a single prism and a corner-cube. Our design is significantly easier to align and tune compared with previous designs. Angle-tuning the prism wavelength-tunes, and translating the corner cube varies the group-delay dispersion over a wide range. When tuned, the device automatically maintains zero angular dispersion, zero pulse-front tilt, zero spatial chirp, and unity magnification. The device can easily be built so that its output beam remains collinear with the input beam, and when the input beam or pulse compressor moves, the input and output beams remain collinear.

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References and links

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1. Introduction

Group delay dispersion (GDD) is a ubiquitous, and often irritating, phenomenon in ultrafast laser labs. When ultrashort pulses propagate through dispersive media, their frequency components emerge at different times due to GDD, causing the resulting pulse to be chirped and stretched and reducing the pulse's peak power. This effect can be compensated by using a *pulse compressor*, which can introduce negative GDD.

The most common method for introducing negative GDD is through angular dispersion. Martinez, et.al. [1] showed that angular dispersion, regardless of its sign, yields negative GDD. Therefore, simply propagating the pulse through a prism or diffracting it off a grating (but we will, for simplicity, discuss only prism devices here) yields negative GDD, whose magnitude depends on the propagation distance. But the output pulse has inconvenient angular and spatial dispersion. Adding a second identical prism, anti-parallel to the first one,

eliminates the angular dispersion from the output beam [2]. Eliminating the spatial dispersion requires propagation through an additional identical pair of prisms (see Fig. 1). As a result, the *four-prism pulse compressor* can compensate material dispersion and also reconstruct the beam. It also compensates for the pulse-front tilt that it introduces in the process. As a result, the pulse compressor is an indispensable tool in essentially all ultrafast labs. It has been used in many ultrashort pulse applications, for over two decades and it has been simplified to two prisms through the use of a mirror after the second prism.

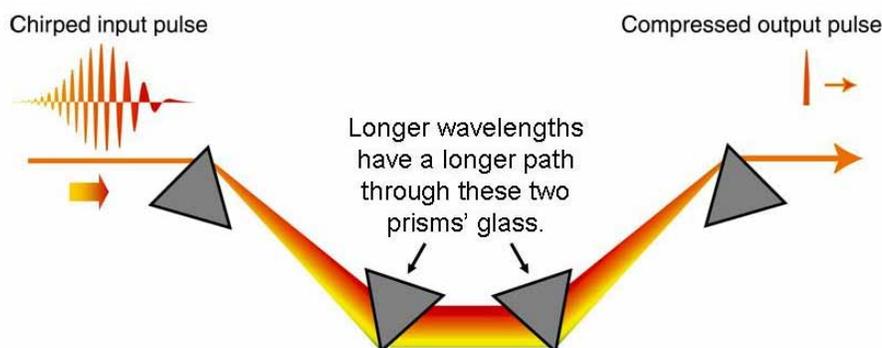


Fig. 1. Pulse compressor, which has negative GDD. Longer wavelengths traverse more glass. The use of two prisms and a mirror simplifies the device somewhat, but it remains difficult to vary its GDD over a wide range and to tune it.

Unfortunately, the pulse compressor is as unwieldy as it is essential. While the GDD can be conveniently fine-tuned by translating one of the prisms into or out of the beam, to vary the GDD over a wider range of values, the separations between the first and second prisms and the third and fourth prisms must be varied (and maintained precisely equal), which involves several alignment parameters and an unwieldy set up. Also, pulse compressors have stringent alignment conditions, and, when not perfectly aligned, they yield an output pulse with residual amounts of spatio-temporal distortions [3] including angular dispersion, pulse-front tilt, spatial chirp, and one-dimensional beam magnification or demagnification (yielding an elliptical output beam). Because pulse compressors must generate massive amounts of these distortions in order to operate, even residual amounts of them can be a serious problem. It is also very inconvenient to tune in wavelength: if the input wavelength changes, all the prisms must be carefully rotated by the same amount, or else all of the above distortions occur. Finally, the device is bulky. To obtain the desired amount of negative GDD, the prism or grating separations can be quite large.

The two-prism design is more compact and slightly easier to tune (only two prisms must be rotated by precisely the same amounts). However, it inherits most of the unwieldiness and propensity for spatio-temporal distortions of the four-prism design.

2. An extremely simple single prism pulse compressor

In this work, we introduce an extremely simple *single-prism pulse compressor*. It simply involves placing a corner cube after the first (and only) prism, which yields an inversion in the reflected beam and so effectively inverts the prism for the second pass (see Fig. 2). Then, by using a periscope as in ordinary two-prism compressors (changing only the height of the beam, not the order of colors), we return the beam through the prism and corner cube for a total of four passes in all. The result is a complete pulse compressor using a single-prism.

This design has all the positive features of standard two- and four-prism compressors. It can achieve variable GDD by translating the prism into or out of the beam. It also achieves all passes through the prism near its tip, minimizing the positive GVD due to the prism glass.

It also has many advantages over conventional two- and four-prism designs. It is significantly easier to align due to the corner cube, which automatically returns the beam anti-parallel to the beam entering it. It can be GDD-tuned over a broad range of values by translating only the corner cube (prism translation can also be used for fine-tuning if desired, but it is not necessary). It achieves wavelength tuning –aligning the device when the input wavelength is changed- by simply rotating the single prism (not two or four prisms, as in conventional designs). It is also very compact: because the beam double-passes the prism corner-cube path, it is about half the size of two-prism design and a fourth the size of four-prism design. Most importantly, it also *precisely* compensates for all of the spatio-temporal distortions—angular dispersion, spatial dispersion, and pulse-front tilt—in the output beam. Finally, it automatically yields unity magnification.

These features make this pulse compressor ideal for essentially all extra-cavity ultrafast-optical applications, and especially for multi-photon imaging apparatuses. We would like to note that *single-grating* pulse stretchers/compressors have been developed previously, but only for very specific applications (chirped pulse amplification) and without these convenient features. [4] The use of a corner cube and a single prism to build a complete pulse compressor appears not to have been mentioned previously, to the best of our knowledge.

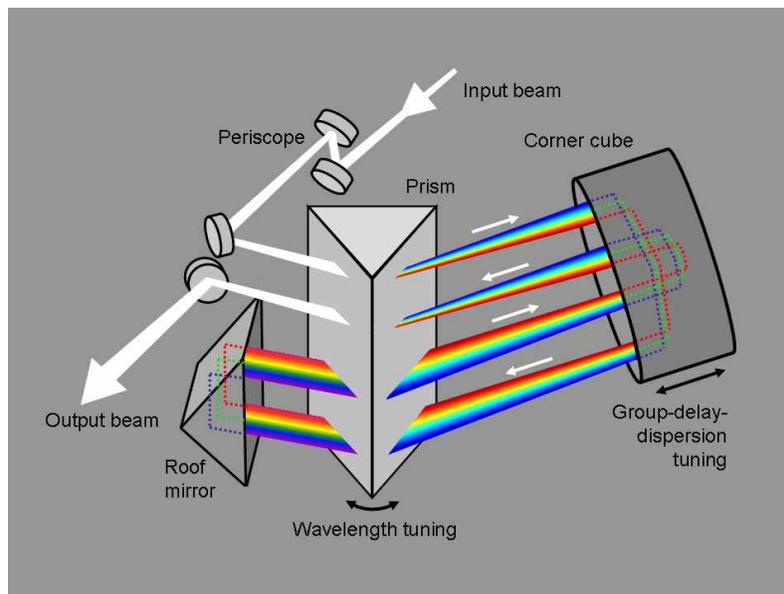


Fig. 2. Single-prism pulse compressor.

3. Wavelength tuning the single-prism pulse compressor

One of the biggest advantages of our single-prism design is the ease of wavelength-tuning. The device can be built for one wavelength, and then, when the input wavelength is tuned, one needs simply to rotate the prism. The beam path through the device remains intact. In short, one can wavelength-tune the single prism-pulse compressor with a single knob; no gears or belts are necessary to maintain proper angles of two or more prisms. Figure 3 shows the required prism rotation, as the input angle is tuned. Note that, if the device is designed for the angle of minimum deviation at a certain wavelength, it can be tuned only to longer wavelengths (rotating the prism in either direction will tune to longer wavelengths).

While this pulse compressor is very easy to wavelength-tune, there are several subtleties associated with tuning (identical to those for all other pulse compressors). We must consider: 1) the magnification; 2) the angular dispersion at the output; 3) the spatial dispersion and the pulse-front tilt at the output; 4) the device throughput; 5) the size of the device; and 6) the effects of beam walk. We show below how our device considerably simplifies nearly all of these issues in the subsections below.

3.1 Magnification

As the wavelength is tuned by rotation of the prism, each pass through the prism will involve incidence and exit angles other than Brewster's angle. While the one-dimensional magnification through a prism is unity when its incidence and exit angles are equal (i.e., Brewster's angle for an ideal pulse compressor), this is not the case for other incidence angles. Indeed, when a prism's incidence angle exceeds its exit angle, some one-dimensional magnification occurs, and when the opposite occurs, demagnification occurs. Thus, away from the ideal Brewster-angle case, each pass through the prism will yield some one-dimensional magnification or demagnification in the beam. This problem exists in all prism and grating pulse compressors, and it must be addressed in the alignment procedure.

In our single-prism design, as the wavelength is tuned, the first pass through the prism will introduce, say, some magnification. However, after the beam returns from the corner cube, the beam will retrace its path and experience demagnification by exactly the same amount because the input/output angles are reversed as compared with the first pass. As a result, if M_i is the magnification after the i^{th} pass through the prism, we will have:

$$M_1 = \frac{1}{M_2} = M_3 = \frac{1}{M_4} \quad (1)$$

Multiplying all four magnifications together yields the overall magnification of the device, which will always be unity. As a result, our single-prism pulse compressor automatically retains unity magnification as the wavelength is tuned. Experimentally, we measured the magnification of the device by measuring the input and output spatial profiles of the beam on a CCD camera. Our measured magnification value is 1.01 ± 0.02 .

3.2 Angular dispersion

It is also crucial that the output angular dispersion remain zero as the GDD and/or the wavelength 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 the variation of the prism angle with wavelength-tuning could cause the output angular dispersion to be nonzero, as it easily can in current pulse compressors. The angular dispersion introduced by a prism depends on which direction the beam propagates through it. It is easy to show that, if a prism has dispersion D and magnification M in the forward direction, it has dispersion MD in the reverse direction. Thus, the angular dispersion added on each pass through the prism is:

$$MD_1 = -D_2 = -MD_3 = D_4 \quad (2)$$

where the minus signs take into account the beam flips.

The total dispersion of a four-prism sequence with non-Brewster incidence angles is described by a complex formula in terms of the prism apex and incidence angles, and so it is difficult to see immediately what the total dispersion of the device would be. However, a little-known simple result [5] gives the total dispersion of an arbitrary sequence of prisms in terms of only the prisms' dispersions and magnifications: the total dispersion is the sum of the individual dispersions, each weighted by the reciprocal of the total magnification that follows

it. So the angular dispersion for an arbitrary sequence of four prisms and hence the dispersion at the output of the single-prism pulse compressor will be:

$$D_{tot} = \frac{D_1}{M_2 M_3 M_4} + \frac{D_2}{M_3 M_4} + \frac{D_3}{M_4} + D_4 \quad (3)$$

Substituting the values for the dispersion and magnification given earlier, it is easy to see that the total device dispersion is necessarily identically zero, independent of the prism angle!

3.3 Spatial chirp and Pulse-front tilt

The symmetry of the device implies that the spatial chirp is also identically zero. This requires proper alignment of the mirror pair, but this is a relatively easy component to align. Also, when the spatial chirp and angular dispersion are zero, the pulse-front tilt must also be zero.

We measured the spatial chirp and pulse-front tilt at the output of the pulse compressor using GRENOUILLE [6, 7]. The shear in the GRENOUILLE trace (indicating spatial chirp) was ~ 0.05 , essentially at the detection limit. We measured the pulse-front tilt angle to be less than $16 \mu\text{rad}$. We can compare this value to that of a two- or four-prism design, in which, typically, a ~ 1 degree misalignment in a prism causes a pulse-front tilt angle of $> 2000 \mu\text{rad}$ [3].

3.4 Throughput

As with any pulse compressor, we must also consider the throughput as the wavelength is tuned. And in this case, our pulse compressor's issues and hence results are identical to those of two- and four-prism compressors. But we will repeat them here for completeness. In order to minimize the Fresnel reflection losses on prism surfaces, prisms can be built and used in Brewster's configuration. This way, if the input light is horizontally polarized, there will be no reflection losses. Brewster's configuration, is however, satisfied only for a particular wavelength. Therefore, as the prism is rotated for wavelength tuning, the throughput of the device will decrease. We calculated that the Fresnel losses remain reasonably small when the device is tuned from 700 nm (at Brewster's) up to 1100 nm. Figure 3 (right) shows the calculated throughput, as a function of input wavelength. Note that throughput can be optimized at some other wavelength, if desired. In principle, anti-reflection coatings could further increase the throughput.

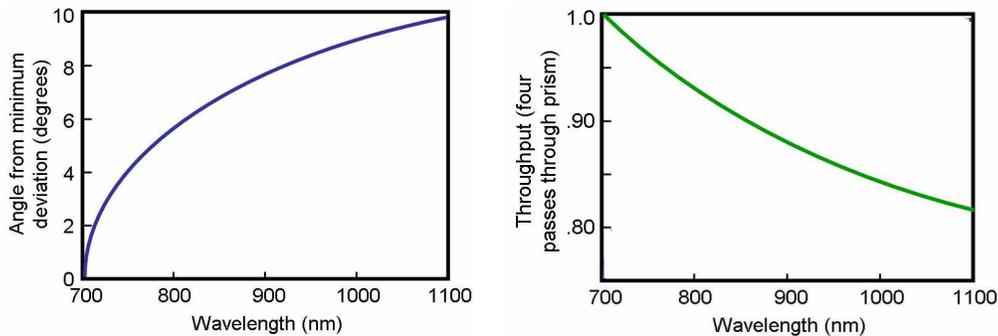


Fig. 3. The prism angle and system throughput (after four passes, not counting imperfect mirror reflectivity) vs. wavelength for single-prism pulse compressor designed using the highly dispersive material, PBH71.

3.5 Size

Just as for the two- and four-prism designs, the size of the pulse compressor in our design is determined by the required negative GDD and also the type of the prism used. Of course, for a given GDD and prism material, our design will be roughly one half or one fourth the size of these conventional devices. Figure 4 shows a theoretical plot of output GDD, as a function of prism-corner cube separation. It is clear that prisms made of dispersive materials, such as SF14 or PBH71 (Ohara Equivalent of SF66), provide significantly higher negative GDD over relatively small separations. Therefore, these dispersive prisms can make the pulse-compressor even more compact.

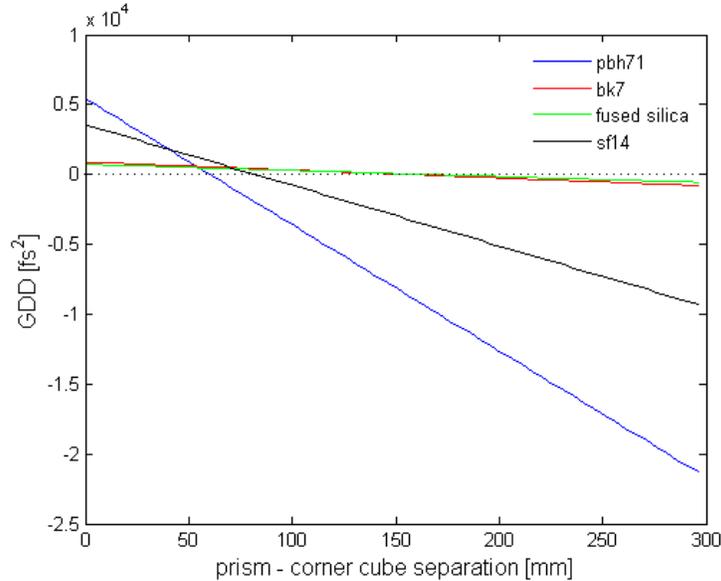


Fig. 4. The change of output GDD in our pulse compressor design, as the prism – corner cube separation is varied, for different prism materials. Propagation through a total of 20 mm prism material is assumed.

The use of dispersive prisms may become disadvantageous when the laser bandwidth is too large. In that case, higher-order dispersion becomes significant. Third order dispersion, for example, causes satellite pulses in the time domain, which may be undesired. In this case, using a less dispersive prism can solve the problem, even though it increases the size of the device.

3.6 Beam walk

Finally, our design has yet another important convenience. When the device is designed as in Fig. 2, the output beam is collinear with the input beam (as is also possible with conventional pulse compressors). In our device, however, if the input beam or the pulse compressor moves up, down, right, or left, the output beam also moves in the same direction, and by the same amount. This makes the device very easy to place in or remove from a beam path.

4. Experiment

We built two single-prism pulse compressors. One with a PBH71 prism, for pulses up to ~35 nm bandwidth, and one with a BK7 prism, for pulses with larger bandwidths. We used corner cubes from PRO Systems, made using silver coated mirrors. Their angular tolerance was 3 arc-seconds, guaranteeing that the output dispersion was essentially zero. The corner cube

also leaves the pulse's polarization intact. The periscope that we use at the output changes only the beam height and hence does not affect the polarization either. However, the last mirror that we use to make the output beam collinear to the input could, in principle rotate the polarization slightly. This can easily be avoided by using the first mirror's highly reflective surface (the one that steers the input beam towards the prism) as the last mirror also. This simply requires a highly reflective coating on one surface and an anti-reflective one on the other. Hence, this mirror becomes an effectively "infinitesimally" thin mirror. This way, the pulse compressor yields the same polarization as the input. A second AR-coated beam-steering compensator plate could also be used to restore input-beam-output-beam collinearity. Experimentally, we measured polarization rotation caused by the pulse compressor to be less than 0.31 degrees. Alternatively, using a periscope at the input of the device also naturally yields a device with zero polarization rotation.

To test these devices, we used Ti:Sapphire laser-oscillator pulses and measured the intensity and phase of the pulses using a Swamp Optics GRENOUILLE [8] before and after the pulse compressor. We measured the GDD as we varied the prism-corner cube separation. Figure 5 shows the measured GDD at different prism-corner cube separations, as well as what we expect from theory. The plot at the top is for PBH71 and the one at the bottom is for BK7. In both cases, we find good agreement with theory. With the use of dispersive PBH71 prisms, we can compensate for 15000 fs² GDD in only 30 cm of prism-corner cube separation. This much GDD is more than that required by most multi-photon microscopes.

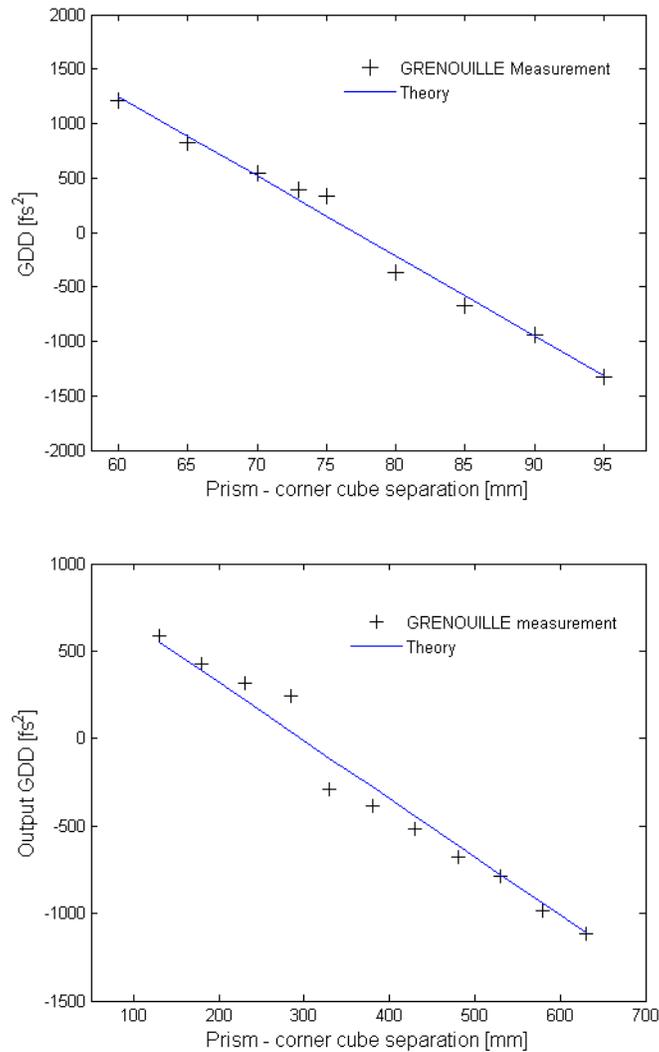


Fig. 5. GDD vs. prism – corner cube separation for single prism pulse compressor. Top: with PBH71 Prism, Bottom: with BK7 Prism. The GDD values have more noise near zero because small amounts of chirp cause only small changes in the pulse length.

5. Conclusion

In conclusion, we have developed an elegant single-prism pulse-compressor design by using a corner cube. Our design is very compact—about a fourth or a half the size of previous designs. It is very easy to tune in wavelength and dispersion, requiring only a single knob for each. It automatically yields zero angular dispersion, zero spatial dispersion, zero pulse-front tilt, and unity magnification. With the use of dielectric mirrors everywhere except for the corner cube, we can achieve an overall throughput of about 75%. We believe that our design can be conveniently used in all ultrafast laser labs, replacing the previous, unwieldy, larger designs.

Acknowledgments

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