Application Note

Dispersion Compensation using Chirped Mirrors

Dispersive media are characterized by a frequency-or wavelength-dependent index of refraction. An optical pulse propagating through such media will have a carrier frequency moving forward at the phase velocity and a pulse envelope moving forward at the group velocity. Because the velocity of the different frequency components that constitute the pulse envelope is also frequency-dependent, the pulse envelope will change in shape. Dispersive effects occur for pulses of any shape, however, the analysis of pulse propagation through optical materials becomes particularly simple assuming that the pulse has a Gaussian shape. Optical pulses generated by mode-locked lasers are very close to being Gaussian which makes them mathematically tractable, therefore, all the equations presented below are based on this shape.

The pulse duration of an optical pulse at full-width half maximum (FWHM) after propagating through dispersive media, Δt_{out}, is given by[1]

$$\Delta t_{out} = \frac{\sqrt{\Delta t^4 + 16(ln2)^2\phi_2^2}}{\Delta t} \quad (1)$$

where Δt describes the pulse duration before propagation and ϕ_2 describes the group delay dispersion (GDD) given by

$$\phi_2 = \frac{\lambda^3}{2\pi c^2}\left(\frac{d^2n(\lambda)}{d\lambda^2}\right)L \quad (2)$$

where L is the length of propagation through the dispersive media, λ is the pulse center wavelength and n(λ) is the index of refraction. Optical pulses will be broadened after propagation through dispersive media, high-index glasses being more dispersive, with the Gaussian pulse shape being preserved. The second derivative of the wavelength dependent index of refraction is calculated from a dispersion equation typically in the Sellmeier form and is evaluated at the pulse center wavelength. GDD can be expressed completely in terms of observables (i.e. pulse width and spectrum) by replacing the transform-limited pulse duration with the spectral bandwidth of the pulses in equation (1),

$$\varphi_2 = \frac{1}{4(\ln 2)}\sqrt{\left(\frac{c_B \Delta t_{out}}{\Delta\nu}\right)^2 - \left(\frac{c_B}{\Delta\nu}\right)^4} \quad (3)$$

where $\Delta\nu = \frac{c\Delta\lambda}{\lambda^2}$ and c_B = 0.441 for Gaussian pulses.[2]

For optical pulses shorter than approximately 30 fs, the frequency dependence of the GDD will also result in pulse-shape altering effects. This effect, known as third-order dispersion (TOD), is associated with the third derivative of the refractive index with respect to wavelength and is given by:

$$TOD = \frac{1}{c}\left(\frac{\lambda}{2\pi c}\right)^2\left(3\lambda^2\frac{d^2n}{d\lambda^2} + \lambda^3\frac{d^3n}{d\lambda^3}\right) \quad (4)$$

After TOD, in addition to pulse broadening, the Gaussian pulse shape will not be preserved.

A detailed derivation of the above equations can be found in Newport's Application Note 29 [see refs. 2 and 3]. In order to calculate the pulse broadening effects from a variety of commonly used optical materials, the Application Note 29 also provides a comprehensive table of refractive indices vs wavelength as well as the first, second, and third order derivatives of the Sellmeier equations of commonly used glasses along with the resulting GDD and TOD.

Dispersion Compensation Using Chirped Mirrors

The section above provides the mathematical expressions that enable the prediction of optical pulse broadening effects after propagation through dispersive media. A variety of optical configurations have been used in the past for the compensation of pulse dispersion. These configurations provide negative GDD necessary to compensate the positive GDD resulting from propagation through optical media. This Application Note will briefly introduce a number of configurations, however, it will mainly be concerned with the use of chirped mirrors.

Diffraction grating pairs have been used in the past to provide negative GDD. Different frequencies, or wavelengths, cover a different propagation distance through the pair because they diffract at slightly different angles. However, the adjustment of dispersion through a zero value (change of GDD sign) is complicated, and relatively large optical losses are introduced preventing the placement of diffraction grating pairs inside laser cavities.[4] A more commonly used method to easily provide adjustable negative or positive GDD relies on prism pairs[5]. A detailed description of this method can be found in Newport's Application Note 29.[2] This configuration has the advantage of being economical, low insertion loss, applicable to highly energetic femtosecond pulses and has a durable set up. Yet, the prism-pair method introduces third order material dispersion which presents a challenge for pulses shorter than 10 fs.[6] Additionally, any deviation from operation at Brewster's angle increases reflection losses[7] and requires a specific laser polarization. An alternative presented in this Application Note employs chirped mirrors that can be used separately, or combined, to construct a compact and easy to use dispersion compensation apparatus that shares many of the advantages of prism-pair compensators while remaining insensitive to laser beam polarization and introducing very small third order dispersion.

Figure 1 represents the chirped mirror operating principle. A chirped mirror is constructed by depositing multiple stacks of dielectric coatings with two alternating refractive indices of gradually increasing layer thickness resulting in lower reflectivity of longer wavelengths for layers further from the surface, and vice versa. As a result, longer wavelength components within the ultrashort pulse bandwidth will penetrate deeper into the dielectric coating. In similarity to the prism pair, the wavelength-dependent optical path length results in negative (anomalous) GDD.[8,9]

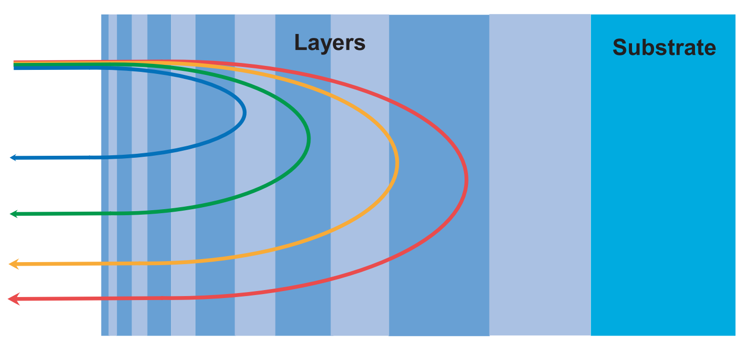


Figure 1- In a chirped mirror, the deeper penetration of longer wavelengths components within the incoming ultrashort pulse into the dielectric coating layers produces a negative GVD.

A well-designed chirped mirror for sub-10 fs applications must have (i) a sustained high reflectivity over a broad spectral range, and (ii) smooth variation of group-delay vs wavelength with minimal fluctuations. Figure 2 shows the predicted reflectance as a function of wavelength for Newport's UF.40 ultrafast chirped mirror. The Figure indicates a reflectance exceeding 95% for the 650 to 950 nm range and in excess of 99.9% for the 700-900 nm range.

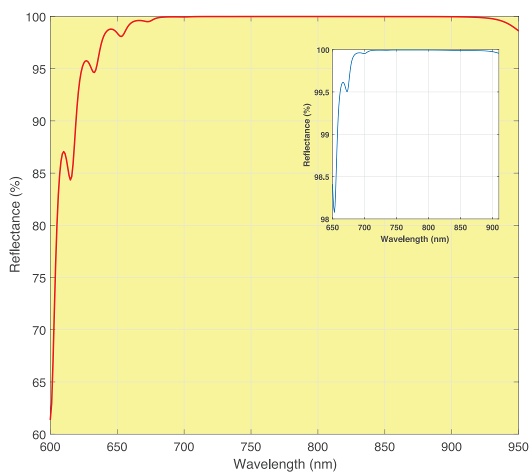


Figure 2. Theoretical reflectance as a function of wavelength for the Newport UF.40 ultrafast multi-layer dielectric coating chirped mirror. The dielectric coating design delivers reflectance that exceeds 99.9 % over the 700-900 nm range.

The theoretical group delay (GD) and group delay dispersion (GDD) are shown in Figures 3 (a) and (b), respectively, for Newport's UF.40 ultrafast multi-layer dielectric coating chirped mirror calculated at a 5° angle of incidence for s and p-polarizations. The GD is not polarization-dependent and has a wide and positively sloped linear region required to obtain a constant and negative GDD. At a wavelength of 800 nm the GDD is approximately -80 fs^2 with the important added advantage of being virtually insensitive to laser polarization. The coating design of dispersion compensation mirrors has inherent oscillatory fluctuations through the active wavelength band. This phenomenon is a natural result of the coating design, however, these oscillations can be cancelled out by using two mirrors that are made such that their oscillations happen at 180° out of phase.

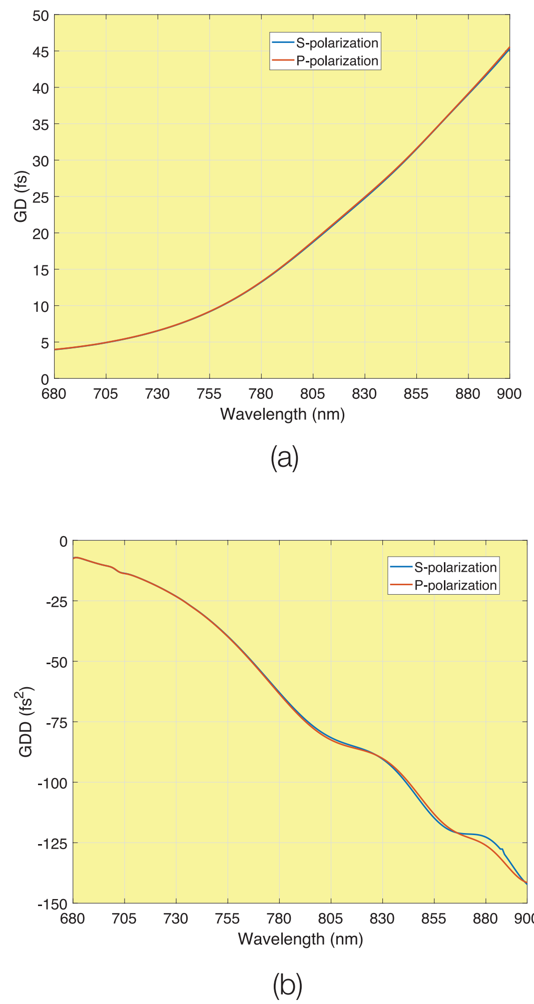


Figure 3. Theoretical GD (a) and GDD (b) for the Newport 10Q20UF.40 ultrafast multi-layer dielectric coating chirped mirror for a 5° angle of incidence.

In contrast to the prism compressor, chirped compensation mirrors have the advantage of providing very low TOD. References [10, 11] list prism separations calculated for a variety of glass materials that result in zero net GDD as well as the TOD introduced by the prism compressor. The listed TOD spans a range of -2000 to 6000 fs^3 depending on the glass material with fused silica being the smallest, and the TOD compensation becomes difficult, or near impossible to accomplish. In contrast, the TOD for the UF.40 mirror shown in Figure 4 indicates 200 fs^3 at 800 nm, i.e. almost a factor of ten smaller than the TOD for fused silica prism compressor.

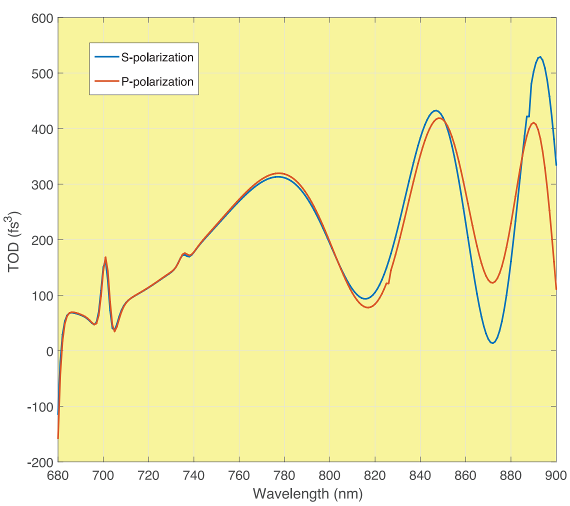


Figure 4. Theoretical third order dispersion (TOD) for Newport 10Q20UF.40 ultrafast multi-layer dielectric coating chirped mirror for a 5° angle of incidence. The chirped mirror delivers no more than 500 fs^3 TOD (cubic term) across the 680 to 900 nm wavelength range.

As mentioned above, a single reflection from a chirped mirror results in a fixed GDD, therefore, additional negative GDD can be provided in proportion to the number of reflections. Figure 5 shows a configuration in which a laser beam is aimed to obtain a controlled number of reflections between two chirped mirrors used to compensate for positive pulse dispersion.

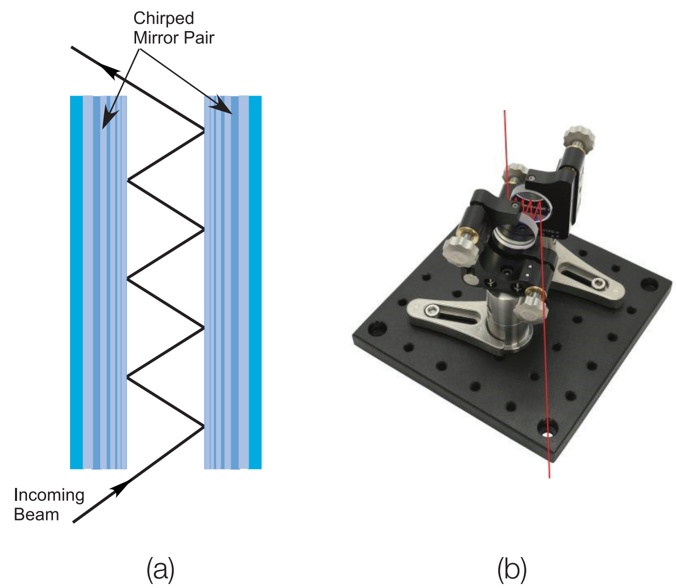


Figure 5. (a) Schematic diagram of a chirped mirror pair configuration (b) Chirped mirror pair mounted into Newport's clear edge mirror mounts U100-A2K to obtain the closest separation between two mirrors and allow for a large number of bounces.

The number of reflections depends mainly on the beam angle of incidence, mirror separation and beam diameter. Figure 6 shows examples of Zemax simulations that predict the number of bounces as a function of these parameters. The simulations assume a minimum clear aperture of 80% of the chirped mirror diameter (25.4 mm) and indicate that a large number of reflections, and hence a large negative GDD, can be realized for beam diameters typical to most lasers.

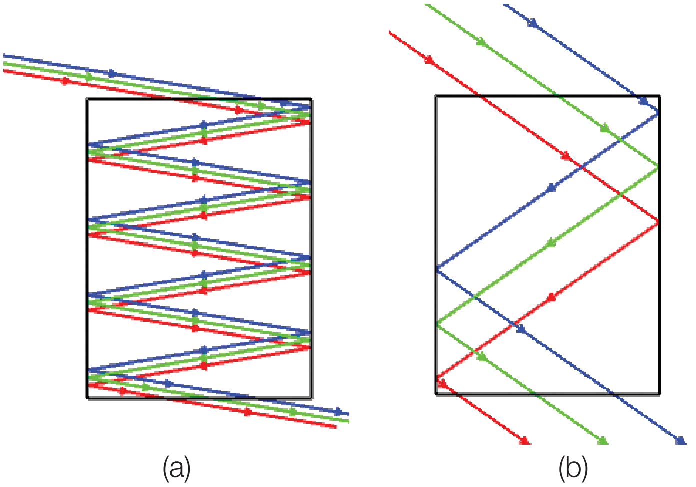
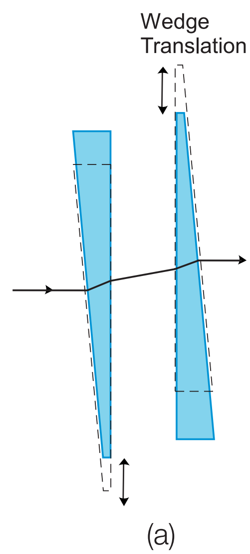


Figure 6. Zemax simulations for a pair of reflective surfaces separated by 15 mm as a function of beam diameter and angle of incidence for: (a) 2 mm, 9.5° and (b) 6 mm, 35°.

The FWHM pulse duration as a function of the number of reflections[12], N, is calculated from an expression very similar to eq. (1),

$$\Delta t_{out} = \sqrt{\frac{\Delta t^4 + (4\ln 2 N\phi_2)^2}{\Delta t^2}} \quad (5)$$

however, in this case the total GDD is given by $N\phi_2$. Since the chirped mirror apparatus provides discrete negative dispersion increments per bounce (-45 and -80 fs^2 at 800 nm for the 10Q20UF.42PAIR chirped mirror pair set and the 10Q20UF.40, respectively), it is recommended that for optimum GDD fine-tuning, a pair of thin fused silica wedges be used in conjunction with the chirped mirror compressor. The use of wedges to provide positive GDD compensation is similar to the adjustment of the path length through the prism apex while using a prism compressor.[3] Figure 7 shows a schematic diagram and the experimental implementation to provide a finely tuned GDD. The use of two identical wedges compensates for angular deviation and insertion losses can be minimized by using the wedges at Brewster's angle. Newport's FemtoOptics Dispersion Wedge family offers two size and glass material choices for this effect: fused silica, 20 x 30 mm, 0.2 mm thick (23RQ12-02) and a BK7, 20 x 50 mm, 0.5 mm thick (25RB12-01UF.AR2). The BK7 prisms are offered with AR coatings for applications over a very broad wavelength range at near normal angle of incidence and have an ultrathin construction with small wedge angles 2.8° or 8°, respectively.



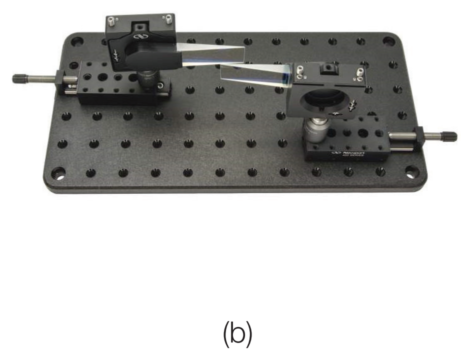
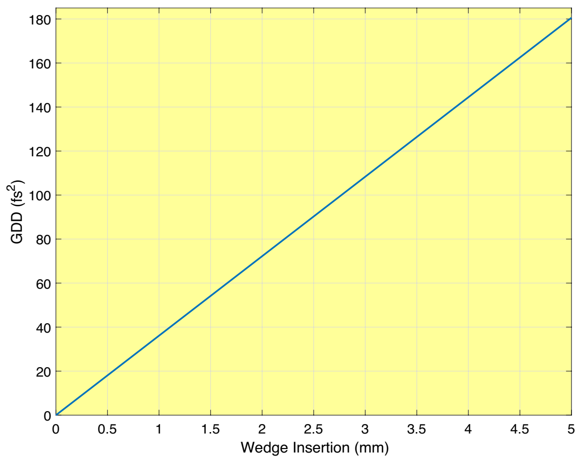
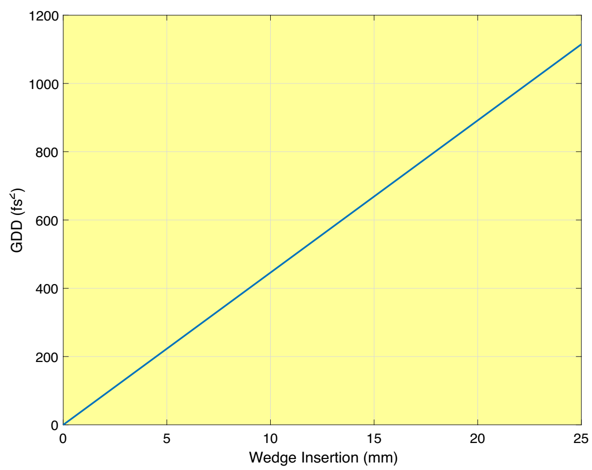


Figure 7. (a) Beam propagation through a pair of identical wedges. The translation of the prism allows the continuous tuning of positive GDD while avoiding angular deviation. (b) Experimental implementation which includes Newport's 25RB12-01UF.AR2-M mounted wedges, HVM-1i top adjust mirror mount, SP-1, 1" optical mounting post, SPH-1 slim optical post holder, 422-1S miniature ball bearing stage, TR-8Q20 adaptors 1/4-20 to 8-32 thread, all mounted on the SA2-06x12 aluminum optical breadboard.

Based on the group velocity dispersion (GVD), which is simply eq. (2) divided by the glass propagation length, for fused silica and BK7 at 800 nm (36.11 fs^2/mm and 44.65 fs^2/mm, respectively) the GDD has been calculated as a function of wedge insertion and graphed in Figure 8 for the 23RQ12-02 and 25RB12-01UF.AR2 ultra-thin wedges.



(a)



(b)

Figure 8. GDD at 800 nm wavelength for an ultrathin dispersion wedge with construction parameters: (a) fused silica glass, 20 x 30 mm, 0.2 mm apex thickness, 2.8° wedge angle (Newport 23RQ12-02) and (b) BK7 glass, 20 x 50 mm, 0.5 mm apex thickness, 8° wedge angle (Newport 25RB12-01UF.AR2).

At full insertion, i.e. at their thickest optical path, the fused silica wedges can be finely tuned over a wide range to compensate a single reflection from the UF.42 chirped mirror, while the BK7 wedge can compensate multiple bounces from the UF.40 chirped mirror.

Alignment of Chirped Mirror Pair Compressor

The experimental setup for chirped mirror pair is shown in Figure 5(b). The chirped mirror pair compressor can be set up as follows:

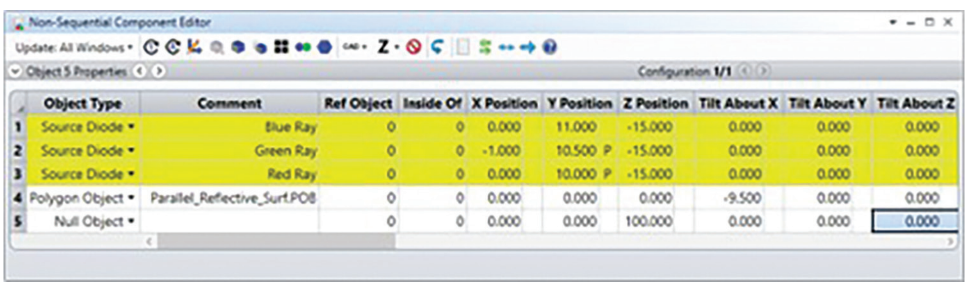
1. Determine the positive GDD responsible for elongating the pulse. This can be accomplished by measuring the spectrum and autocorrelation width, and then calculating the GDD from equation (2).
2. Based on -45 fs^2 per bounce GDD provided by the 10Q20UF.42PAIR, or -80 fs^2 for the 10Q20UF.40, estimate the required number of bounces.
3. Verify that the clear edge mirror mounts have been mounted onto a breadboard or optical table in such a way that the right edge of the chirped mirror is exposed.
4. Prior to reflecting from the mounted chirped mirrors, take care to ensure that the beam is traveling at constant height relative to the table.
5. Insert the first mirror assembly into the beam path and translate the mirror until the laser beam is at the edge of the mirror clear aperture. Adjust the tilt and rotation screws until the reflected beam is traveling at a constant height relative to the table.
6. Install the second mirror assembly as close as possible to the first mirror and translate until the mirror is as close as possible to the incoming laser beam without obstructing its path.
7. Adjust the mirror rotation screws to obtain the desired number of reflections. It may be necessary to do minor adjustments to the tilt adjustment screws to maintain the beam constant height.

Conclusions

The application note describes a chirped mirror dispersion compensator for ultrashort optical pulses of simple and elegant implementation and versatility. The chirped mirror dielectric coating design delivers reflectance that exceeds 99.9 % over the 700-900 nm range making it virtually loss-less. The chirped mirror GD is not polarization dependent and has a wide and positively sloped linear region required to obtain a constant and negative GDD which is polarization independent as well. Newport's chirped mirrors are available with GDD of approximately -45 to -80 fs^2 at 800 nm per reflection, and by controlling the number of reflections, they can easily compensate large positive GDD. The chirped mirror compensator has the added advantage of introducing a fraction of the TOD introduced by other dispersion compensator configurations, which is very difficult to compensate.

Appendix – Zemax model for prediction of number of bounces between two reflective surfaces.

The Appendix provides screenshots of the Zemax Non-Sequential Component Editor and the Polygon Object File used for the prediction of the number of reflections between two surfaces as a function of the surface separation, beam diameter and angle of incidence. For the simulation all distances are specified in millimeters. The beam diameter can be modified by changing the ray offsets using Object 1 for pickup. The angle of incidence can be modified by changing the Tilt About X parameter.



	Object Type	Comment	Ref Object	Inside Of	X Position	Y Position	Z Position	Tilt About X	Tilt About Y	Tilt About Z
1	Source Diode	Blue Ray	0	0	0.000	11.000	-15.000	0.000	0.000	0.000
2	Source Diode	Green Ray	0	0	-1.000	10.500 P	-15.000	0.000	0.000	0.000
3	Source Diode	Red Ray	0	0	0.000	10.000 P	-15.000	0.000	0.000	0.000
4	Polygon Object	Parallel_Reflective_Surf.POB	0	0	0.000	0.000	0.000	-9.500	0.000	0.000
5	Null Object		0	0	0.000	0.000	100.000	0.000	0.000	0.000

Polygon Object File

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! Newport Corporation, August 2019
! Polygon Object
! Parallel Reflective Surfaces
! front face vertices
V 1 -10 -10 -5
V 2  10 -10 -5
V 3  10  10 -5
V 4 -10  10 -5
! Back face vertices
V 5 -10 -10 10
V 6  10 -10 10
V 7  10  10 10
V 8 -10  10 10
! Front Face Vertix Connectivity List, Reflective
R 1 2 3 4 1
! Back Face Vertix Connectivity List, Reflective
R 5 6 7 8 1
! Top Face Vertix Connectivity List
R 4 3 7 8 0
! Bottom Face Vertix Connectivity List
R 1 2 6 5 0
! Left Side Face Vertix Connectivity List
R 1 4 8 5 0
! Right Side Face Vertix Connectivity List
R 2 3 7 6 0
```

References

1. J. Diels and W. Rudolf, Ultrashort Laser Pulse Phenomena, Second Edition (Massachusetts, Academic Press, 2006).
2. Application Note 29, Prism Compressor for Ultrashort Laser Pulses, Mewport Corporation.
3. Technical Note, “The effect of dispersion on ultrashort pulses,” Newport Corporation.
4. R. L. Fork, C. V. Shank, R. Yen, and C. A. Hirlimann, “Femtosecond optical pulses,” IEEE J. Quantum Electron. QE-19, pp. 500, 1983.
5. R. L. Fork, O. E. Martinez, and J. P. Gordon, “Negative dispersion using pairs of prisms,” Optics Letters, Vol. 9, pp.150-152, 1984.
6. M. T. Asaki, C.-P. Huang, D. Garvey, J. Zhou, H. C. Kapteyn, and M. N. Murnane, “Generation of 11 fs pulses from a self-mode-locked Ti:sapphire laser,” Opt. Lett., vol. 18, pp. 977–979, 1993.
7. Diels, J., & Rudolph, W. Ultrashort laser pulse phenomena : Fundamentals, techniques, and applications on a femtosecond time scale, pp. 117, 2006
8. R. Szipöcs and A. Köházi-Kis, “Theory and design of chirped dielectric laser mirrors,” App. Phys. B, vol. 65, pp. 115-135, 1997,
9. Nicolai Matuschek, Franz X. Kärtner, and Ursula Keller, “Theory of Double-Chirped Mirror,” IEEE J. OF Sel. Topics in QE, Vo. 4, No. 2, pp. 197-208, 1998.
10. L. Arrisian and J. C. Diels, “Carrier to envelope dispersion control in a cavity with prism pairs”, Phys. Rev. A 75, pp. 013814 (1-10), 2007.
11. Cristtel Y. Ramírez-Corral , Martha Rosete-Aguilar & Jesús Garduño-Mejía, “Third order dispersion in a pair of prisms,”, Journal of Modern Optics Vol. 56, No. 15, pp. 1659–1669, 2009.
12. I. Matsuda, K. Misawa and R. Long, “Femtosecond chirp-variable apparatus using a chirped mirror pair for quantum coherent control,” Opt. Comm. Vol. 239, pp 181-186, 2004.

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