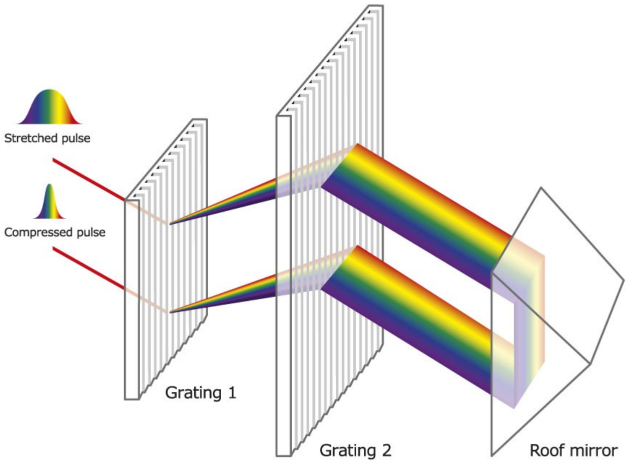
Pulse stretching and compressing using grating pairs

A White Paper



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Dispersion compensation using grating pairs

Reaching the shortest possible pulses is one crucial task of scientists of all disciplines related to ultrafast lasers. Whether to generate the shortest possible pulses from a mode-locked laser or amplifier or simply to maximize the on-target intensity, compensating for temporal pulse broadening that happens due to linear dispersion effects continues to be of crucial importance in ultrafast science.

When a pulse propagates through most common types of materials that form optical components (most commonly dielectrics), the different spectral components that form an ultrashort pulse will not propagate with the same speed. This results in a ***temporal delay*** between the different spectral components of an ultrashort pulse. This effect is called ***group delay dispersion*** or GDD. This temporal rearrangement of spectral components, sometimes also called 'chirp', results in an undesired temporal stretching of the pulse.

Group delay dispersion can be quantified by the second derivative with respect to angular frequency of the *spectral phase,* which is the wavelength-dependent phase accumulated by the different spectral components of a pulse when propagating through a certain thickness of dispersive material.

$$E(z,t) = \frac{1}{2\pi}\int \tilde{E}(z=0,\omega)e^{i\omega t}e^{-i\phi(z,\omega)}\,d\omega \qquad (1)$$

$$\text{GDD} = \frac{d^2\phi}{d\omega^2} \text{ (unit fs}^2\text{)} \qquad (2)$$

Although it is very common to use this expression as a function of angular frequency, it is also sometimes convenient to relate this formula to the wavelength dependent refractive index, because $n(\lambda)$ can be obtained via the Sellmeier coefficients.

$$\frac{d^2\phi}{d\omega^2} = \frac{\lambda^3 L_d}{2\pi c^2}\frac{d^2 n}{d\lambda^2} \qquad (3)$$

It is worth noting that we focus here on the second order dispersion because it is the one that has the strongest influence on the pulse duration. In many cases, higher order dispersion terms can be neglected. However, when dealing with extremely broad spectra, higher order dispersion terms can also have an influence on the pulse.

In most experimental setups, ultrashort pulses are broadened by propagating through materials such as fused silica, quartz, sapphire, etc... For example, a transform limited pulse centered at 800 nm wavelength with 10 fs pulse duration will be stretched to 100 fs after 1 cm of propagation through fused quartz. These materials exhibit ***positive dispersion*** at the typical operation wavelength of ultrafast lasers of ≈ 1µm. This means that the shorter wavelengths in the pulse spectrum will experience a longer delay compared to the longer wavelengths: i.e. 'red' travels faster than 'blue'. Other effects such as self-phase modulation, can also introduce a positive chirp in a similar way to propagation in a dispersive material.

Grating pairs

In order to reach shortest pulses after dispersive propagation, it is possible to compensate this pulse broadening by applying dispersion of the opposite sign, i.e. ***negative dispersion.*** Since most materials at the wavelength of interest have positive dispersion, other means are usually required to achieve negative dispersion.

In this goal, ***grating pairs*** are one of the most commonly used techniques. Compared to other methods to obtain negative dispersion (for example prisms), gratings can achieve much higher values of negative dispersion in compact setups. Furthermore, the development of pure fused-silica transmission gratings capable of generating extremely high-diffraction efficiency, and with very high damage threshold has made this the technique of choice for high-power ultrafast lasers.

A grating pair in its simplest form (the so-called Treacy configuration, see Fig. 1) introduces ***negative dispersion*** due to the difference in the optical path undergone by the different wavelengths. At the output of a grating pair, however, we have a spatially incoherent beam. This can be solved by retroreflecting the light back into the grating pair, additionally generating double the amount of negative dispersion.

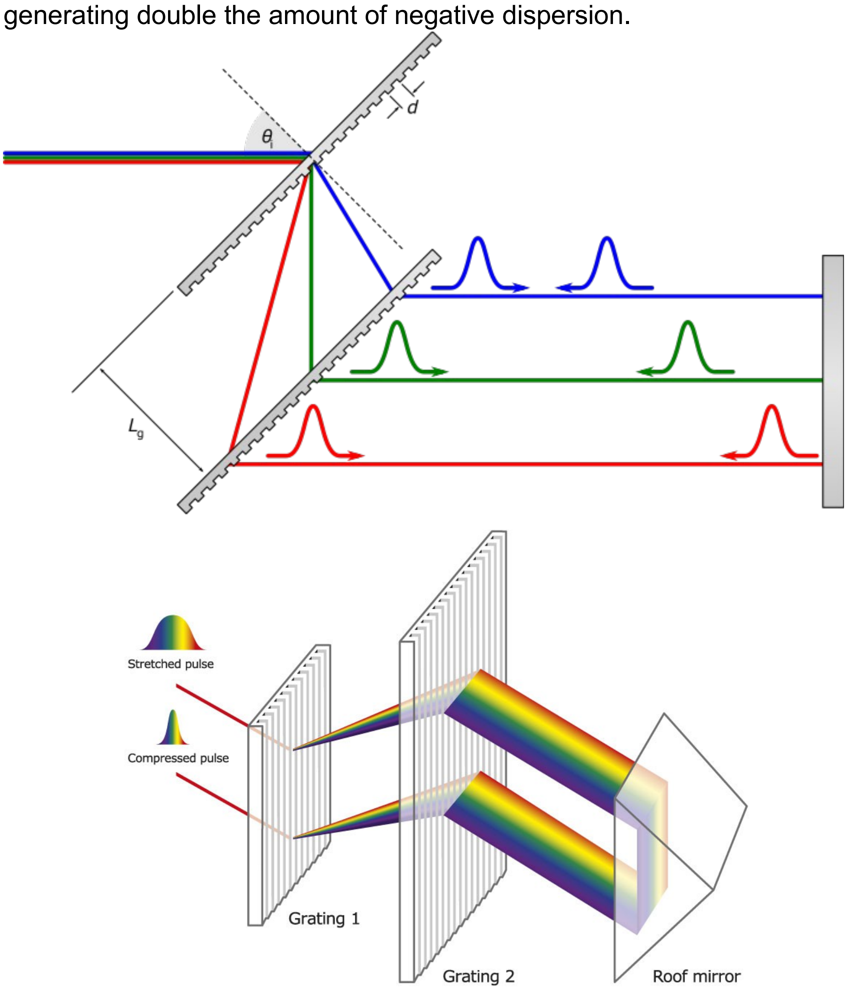


Fig 1 – Principle behind a Treacy stretcher or compressor based on gratings. Top: Schematic view illustrating the concept. Bottom: Possible practical implementation of a compressor using a roof mirror to retroreflect the beam after the first two-grating pass.

The GDD introduced by a grating compressor of this type is given by the following equation:

$$\frac{d^2\phi}{d\omega^2} = -\frac{m^2\lambda^3 L_g}{2\pi c^2 \Lambda^2}\cdot\left[1-\left(-m\frac{\lambda}{\Lambda}-\sin\theta_i\right)^2\right]^{-3/2} \qquad (4)$$

Where m is the diffraction order (usually -1), λ the center wavelength, L_g the distance between the two parallel gratings, Λ the period of the grating and θ_i the angle of incidence on the first grating. In practice, this formula shows that the total negative dispersion introduced can be fine-tuned simply by changing the distance between the gratings.

Remark: This result only takes into account the 'geometrical' dispersion of a pair of prisms. In the special case of transmission gratings and for very short pulses, some ´positive dispersion' might need to be added through propagation through the thin fused silica substrate.

As we mentioned before, this simple configuration can yield only *negative dispersion* and a fixed ratio of second and higher order dispersion. Although in many case this is what one is looking for (see examples below) some cases require for example strongly positively chirped pulses or special control of higher orders of dispersion. In this goal more sophisticated layouts based on this same grating pair concept can be used (Fig 2). The most commonly used arrangement is the so-called Martinez-arrangement where two lenses are placed between the two gratings. The two lenses form a telescope with a magnification factor M = 1, when $L = f$. By adjusting the distances $L < f$, this layout allows to introduce "negative" separations between the gratings, thus achieve ***positive dispersion***. The same formula as above can be used, using the corresponding negative distance L. In the case where the distance L>f this setup is the equivalent of the Treacy grating.

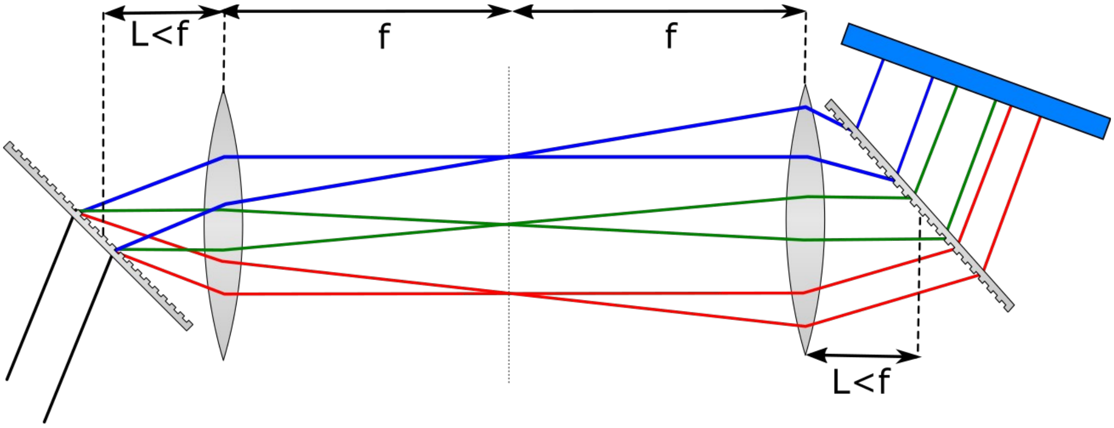


Fig 2 – Martinez stretcher or compressor based on gratings. By adjusting the distances between the lenses and the gratings, dispersion can be also adjusted to positive values, which is not possible with a Treacy grating pair. This setup can provide both positive and negative dispersion, albeit with a larger footprint.

This idea can be extended to apply arbitrary phase elements and even for amplitude shaping of a spectrum by making use of the Fourier plane available between the two-lenses. This plane gives us access to spatially separated components of the spectrum, which can be modified, for example using liquid crystal technology.

Use for stretching or compressing of pulses

Stretcher

It is straightforward to estimate the effect on the pulse duration of a transform-limited input pulse (no chirp). The simplest case is when the pulse is strongly broadened by the grating arrangement (GDD >> τ_p^2, which is very commonly verified), then the following simple formula applies:

$$\tau_p(z) \approx \frac{d^2\phi}{d\omega^2}\Delta\omega_p \quad (5)$$

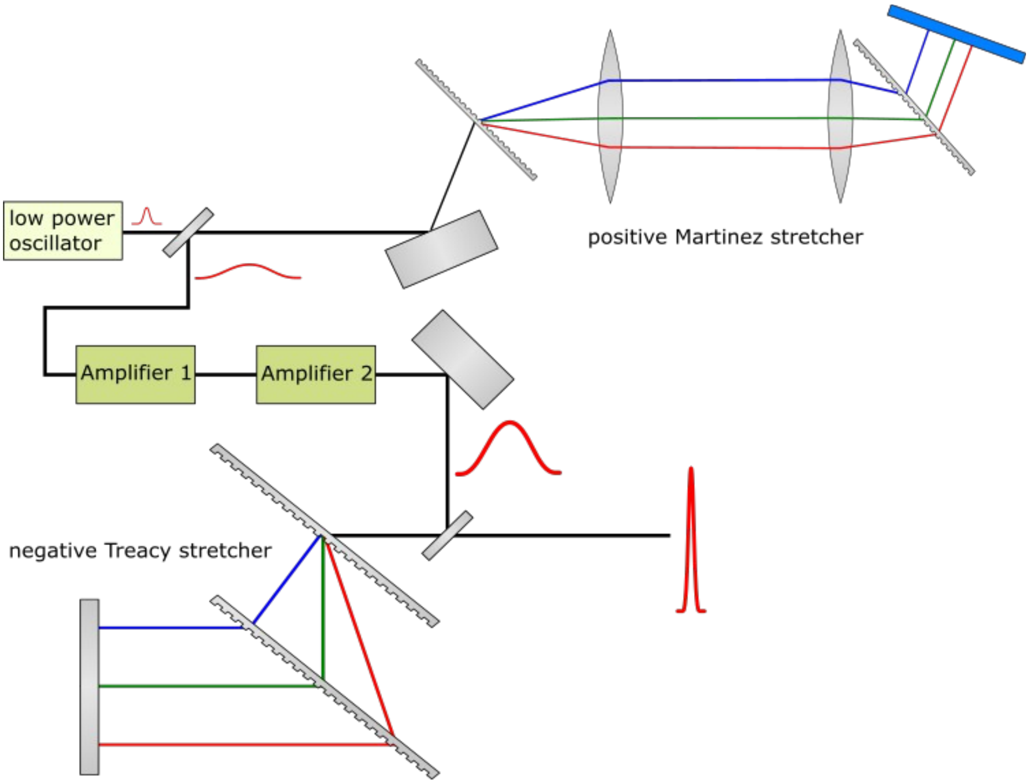
Where τ_p is the pulse duration after the stretcher, and $\Delta\omega_p$ is the bandwidth of the transform limited input pulse in units of angular frequency (related to frequency by $\Delta\omega_p = 2\pi\,\Delta\nu_p$).

Compressor

In this case, the input is a spectrum with a certain chirp, and the goal is to obtain pulses as close as possible to the transform limit at the output of the compressor. Knowledge about the ***chirp of the input spectrum*** is then required to estimate what the effect of the grating compressor will be. In case this chirp is known (for example via a FROG or SPIDER measurement, or simply from a numerical estimation), one simply needs to use (4) to find the grating configuration that exactly compensates for this chirp.

A few important examples:

Chirped pulse amplification



Perhaps the most common use of grating stretchers and compressors is in chirped pulse amplification. In this case, one usually desires strongly ***positively chirped pulses*** at the input of the amplifier, which can be easily achieved with a Martinez-type grating layout. Formula (5) can be used to calculate which grating is arrangement is required to reach the desired long pulses.

After amplification, the pulse needs to be recompressed. In most cases, the amplifier did not introduce any distortions of the spectral phase and the exact opposite ***negative chirp*** needs to be applied. In this case, a Treacy grating is most convenient.

Nonlinear pulse compression

Many experiments make use of nonlinear compression to shorten the pulse duration available from a laser system. Here, the spectrum of a pulse is broadened due to the intensity dependence of the refractive index. The new spectral components that are generated are not in phase, and generally result in longer wavelengths being faster than shorter ones - i.e. a positive chirp. Although, the resulting spectral phase is in this case not purely of second order, significant pulse shortening can be obtained by compensating for the second order dispersion. In this case, Treacy type grating compressors are most commonly used.

About the author

Clara Saraceno was born in Argentina in 1983 and was a student at the Institut d'Optique in Palaiseau, France. After completing her studies she first went into industry from 2007 to 2008, working for a laser manufacturer in the USA. She then continued her academic training in Switzerland, completing a doctorate in Physics at ETH Zurich in 2012 which brought her, amongst others, the 2013 QEOD Thesis Prize, awarded by the Electronics and Optics Division of the European Physical Society. After graduation, Saraceno has worked at ETH Zurich and the University of Neuchatel as a postdoctoral researcher. Most recently, her research work on high-power ultrafast lasers earned her the Sofja Kovalevskaja Award of the Alexander von Humboldt Foundation (2015). In 2016, she was appointed as Professor in the Faculty of Electrical Engineering and Information Technology in the Ruhr University Bochum, where she currently works on various aspects of ultrafast laser science and technology.

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