Characterization of Chirped volume bragg grating (CVBG)

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1 Laser pulses

Ultrashort laser pulses have extremely short pulse duration. When the pulse duration is less than picoseconds $10^{-12}s$, this pulse is called ultrashort pulse. It can be investigated via a time domain and frequency domain. In time domain, the electric field of the electromagnetic wave is expressed as

$$E(t) = A(t)\cos(\phi_0 + \omega_0 t), \tag{1}$$

where $A(t)$ is the temporal amplitude, ω_0 is the carrier frequency and ϕ_0 is the absolute phase. The temporal intensity can be as

$$I(t) = \frac{1}{2}\epsilon_0 A(t)^2. \tag{2}$$

If the pulse exhibits very short duration for example few cycle pulses below $5fs$ with high power, the intensity may reach $10^{16}\frac{w}{cm^2}$.This tremendous amount of energy is more than enough to study non linear process for example high harmonic generation [1]. As a result of that fact, the compression of high power laser pulses becomes a vital process to produce high harmonic generation according to the three step model [2]. The temporal form of ultrashort laser pulse is shown in figure 1

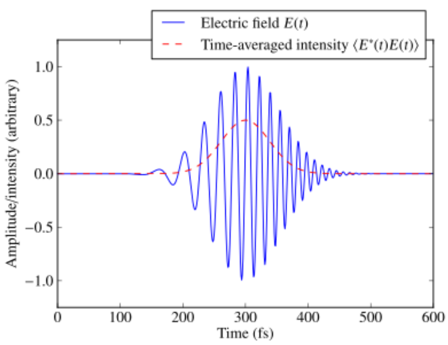


Figure 1: An ultra-short laser pulse in time domain.Ref [4]

The frequency domain form can be obtained via inverse Fourier transform of the time domain. The spectrum of the electric field $E(\omega)$ can be obtained from the inverse Fourier transform of the electric field in time domain

$$E(\omega) = \int_{-\infty}^{\infty} E(t)e^{-i\omega t}dt. \tag{3}$$

The spectrum can be decomposed into amplitude and phase

$$E(\omega) = |E|e^{-i\phi(\omega)}, \tag{4}$$

where $|E|$ is the spectral amplitude, $I(\omega)$ is the spectral intensity and $\phi(\omega)$ is the spectral phase; the phase of electric field in frequency domain.

Most of the lasers pulses are Gaussian pulses [3]. The electric field of the Gaussian pulse in time domain with zero absolute frequency phase can be expressed as

$$E(t) = \frac{E_0}{2}e^{i\omega_0 t}e^{-\ln 2\frac{t^2}{\Delta t^2}}, \tag{5}$$

where Δt is the full width at half maximum $FWHM$ of a corresponding intensity $I(t)$. The spectrum of the Gaussian pulse can be obtained by inverse Fourier transform

$$E(\omega) = \frac{E_0\Delta}{2}\sqrt{\frac{\pi}{2\ln 2}}e^{i\omega_0 t}e^{-\ln 2\frac{t^2}{\Delta t^2}}. \tag{6}$$

$FWHM$ of the temporal intensity profile $I(t)$ and spectral intensity profile $I(\omega)$ are related by

$$\Delta t\Delta\omega = 4\ln 2, \tag{7}$$

where $\Delta\omega$ is $FWHM$ of the spectral intensity profile $I(\omega)$. Equation 7 exhibits the origin of pulse compression. The more the frequency components , the shorter the pulse duration is.

2 Pulse compression

Propagation of ultra-short pulses inside non-linear media has some important features. One of them is the frequency dependence of media refractive index which leads to different phase velocities of the interacting pulses with the media. Group velocity dispersion (GVD) merges as a result. In this way, spectrum is broadened by adding new frequency components to the spectrum [3]. Adding new frequency components results in pulse compression. The spectral phase can be expressed as follow

$$\phi(\omega) = -\beta(\omega)L, \tag{8}$$

where L is the length of the non linear media and β is the propagation constant,i.e. phase shift per unit length. GVD is mathematically expressed by the

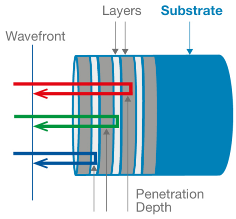


Figure 2: Chirped mirrors.Ref [5]

second order term of Taylor expansion which is measured in units of $[time^2/Length]$. The following equation exhibits the pulse broadening or compression

$$\tau_{out} = \tau_{in}\sqrt{1 + \left(4ln2\frac{GDD}{\tau_{in}^2}\right)}, \tag{9}$$

where $GDD = GVD \times L$ (i.e, the group delay dispersion). From equation 9 an important fact can be deduced. If there is a positively chirped pulse and a negative GVD then pulse compression can be obtained. The fused silica fibers have a positive GVD for any wavelength shorter than $1300nm$. GVD in $800nm$ is positive for the fused silica fibers, i.e. $36.11fs^2/mm$.[3]

Dispersion compensation after spectrum broadening is an essential requirement to get pulse compression. The most important method for that purpose is using the idea of wavelength dependence on the penetration depth. The reflected mirrors which can be used in high power laser reflection should have some important features. These features are summarized as the high reflectance over broad spectral bandwidth and the damage threshold.

Chirped mirrors CMs figure 2 are dielectric mirrors which contain multi layers. The essential idea of CMs is the wavelengths dependence of the penetration depth in multilayer coating. Different wavelengths are reflected from different coating depth for different wavelength means that different GDD. The negative GDD means that the longer wavelength is reflected from far multilayer. For example, the GDDD from a pair of CMs is $30-100fs^2$ for a few millimeter of glass. The positive GDD that is obtained from propagation of $800nm$ pulses in non linear media can be compensate by using negative CMs. Figure 2 shows the working principle of CMs

2.1 Diffraction grating pair

The compression by diffraction gratings is based on the frequency dependence of the phase as far as as the quadratic frequency term. The total temporal phase can be expressed as follow

$$\phi(t) = \phi_0 + \omega_0 t + \phi_a, \tag{10}$$

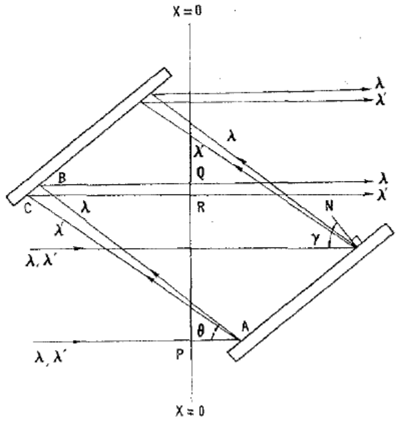


Figure 3: Diffraction gratings for pulse compression and stretching.Ref [6]

where ϕ_a is the quadratic time dependent function

$$\phi_a(t) = bt^2, \tag{11}$$

where b is the chirp parameter. Chirp means that the carrier frequency of the pulse is a function of time. The group delay is represented by the higher term of the taylor expansion of the phase

$$g(t) = \omega t + \phi_a \tag{12}$$

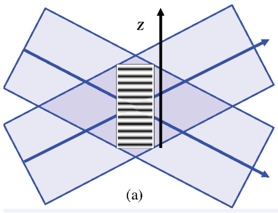
Figure 3 shows the geometrical arrangement of diffraction grating pair used to compress the pulse. The ray paths are shown for two wavelength components with $\lambda^{'} > \lambda$. Since the path length for $\lambda^{'}$ is greater than that for λ, longer wavelength components experience a greater group delay. In this way the pulse can be either compressed or stretched by introducing the suitable group delay velocity by gratings.[6]

In this way , the pulse can be either compressed or stretched according to the geometry of the diffraction gratings. the use of a diffraction gratings pair permits measurements sensitive to the phase structure of ultrashort optical pulses to be made as well as providing a simple method compressing pulses with the appropriate phase characteristics.

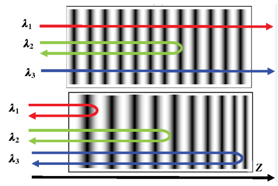
3 Chirped volume Bragg gratings (CVBG)

Volume Bragg gratings are Bragg gratings which are written inside some transparent material, e.g. in the form of a cube or a parallelepiped . Typically, such gratings are written into some photosensitive glass, and sometimes into crystal materials. They are also called bulk Bragg gratings or volume holographic gratings.[9]

Chirped volume Bragg gratings (CVBG) exhibit a wavelength-dependent group delay, which can be utilized for pulse stretching and compression as explained the previous part.The operation principle is essentially the same as for



(a) Recording geometry for gratings by interference of collimated beams.



(b) Schematics of beam diffraction by volume Bragg gratings.

Figure 4: Chirped volume brag gratings CVBG .Ref [7]

chirped mirrors as explained in the previous parts. The obtained range of group delay can be far larger – e.g. many picoseconds. The group delay dispersion can also be far larger. Depending on the orientation of the device, the group delay dispersion for reflected light may be positive or negative.

CVBG introduce a periodic modulation of the refractive index in some region. This modulation is resulted from the interference pattern which is produced from interference between two collimated beams as shown in figure 4a.As shown in figure 4b, CVBG has the same working principle of CMs if the Bragg condition of reflection is approved [7].

4 Characterization of CVBG

In the experimental task, a new CVBG was under test for the first time. The spectrum profile and power efficiency has been tested. As shown in figure 5, the laser source which was used in the experiment, was high power laser system. As an amplifier media, Yg:KYW [8] has been used to obtain high average power and high quality spatial beam distribution. As a system pros, the power is high enough to characterize the new CVBG. A set of dichoric mirrors has been used to reflect the beam. The mirror reflection is 99.9 at $\lambda = 1030nm$. The beam power can be attenuated by the means of combination of half wave plate and thin film polarizer (TFP). Under the condition of small beam size, the power is too high. This drives us to increase the beam size by the means of a telescope with a focusing lens ($f = 150mm$) and defocussing lens ($f = -75mm$). Consequently, the beam size is doubled.

The reflection and transmission of the beam is controlled by an optical combination. This combination contains half wave plate, quarter wave plate, Faraday cell and thin film polarizer. CVBG is fixed between the second TFP and the mirror. The power is measured by a coherent energy meter as shown in figure 5. The beam profile was observed via a camera with objective.

Figure 6 shows the characterization of pulse duration before inserting the CVBG. The measured pulse duration is around $580fs$ in figure 6a. The quality of the beam profile is shown in figure 6b. The spectrum of the input beam has been measured by a spectrometer as shown in figure 6c. The bandwidth at

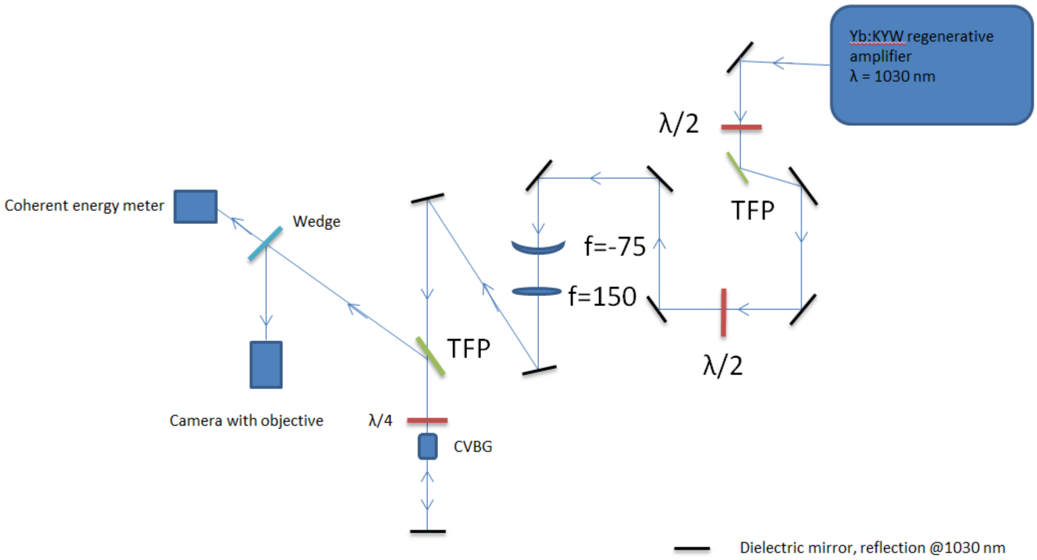
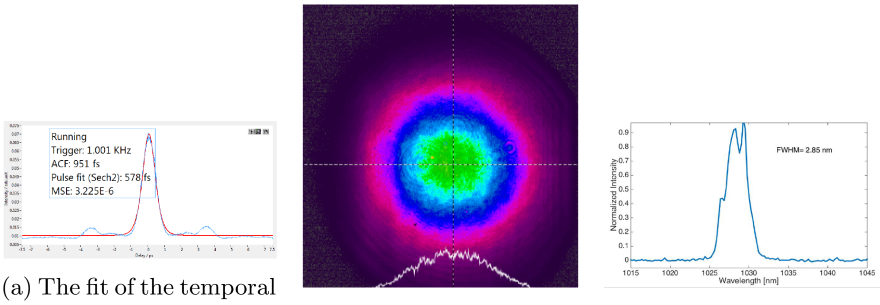


Figure 5: Experimental set up for beam characterization.



(a) The fit of the temporal pulse.

(b) The beam profile.

(c) The beam profile.

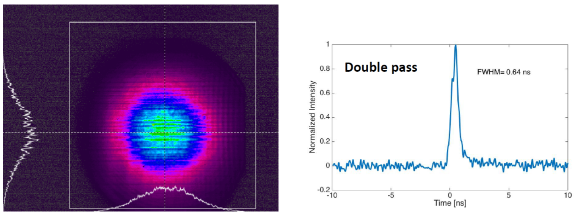
Figure 6: Beam characterization without CVBG

FWHM is $2.85nm$.

CVBG is fixed between the second thin film polarizer and the mirror with 0 degree reflection as shown in figure 5. The beam profile has been observed after the first pass in the CVBG. Figure 7a shows the beam profile with single diffraction The extension ratio of CVBG is around $100ps/nm$. One single pass introduces broadening in the pulse duration around $300ps$. As a result of that fact, the spectrum range is not in the range of spectrometer. For this reason, a double pass measurements has been carried out to get double broadening around $600ps$. The temporal pulse duration after double pass is shown in figure 7b.

5 Summery

The chirped volume bragg gratings has been tested for the sake of pulse compression and stretching. In comparison with the gratings pair, CVBG introduce



(a) The beam profile of single diffraction.

(b) The temporal profile after double pass.

Figure 7: Beam characterization with CVBG

the same purpose with less distance. For this reason, the power test is highly important in addition to the beam profile test. This test will draw up a comprehensive figure for the geometry of CVBG compressor and stretcher.

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