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Time-compensated grazing-incidence monochromator for extreme-ultraviolet and soft X-ray high-order harmonics

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ABSTRACT The use of a grating monochromator for the selection of one or more high-order laser harmonics produced by a femtosecond pulse interacting with a gas jet may alter the duration of the pulse itself. This is due to the differences in the optical paths of the rays caused by ordinary diffraction when a grating is used. The time stretching can be almost eliminated by using two gratings in time-compensated configurations. Unfortunately, the classical diffraction mounting has low efficiency, overall in the extreme-ultraviolet region. High broadband efficiency can be obtained by using the conical diffraction mounting. A time-compensated monochromator with toroidal gratings used in conical diffraction is here presented. It is shown that the time compensation is very effective in a broad spectral region, ranging from VUV to soft X-rays, with much higher efficiency than the classical diffraction mounting.

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1 Introduction

Laser high-order harmonics (HH) have unique characteristics in terms of very short duration, discrete plateaulike spectra up to the water window, small divergence, spatial and temporal coherence, and high brightness [1–5]. The time duration of the harmonics is shorter than the laser pump pulse duration because of the nonlinearity of the process that tends to restrict the effective part of the pump [6]. The use of such a radiation is potentially very promising for fundamental sciences: ultrafast pulses are required for high-resolution pump-probe experiments or for maximizing the instantaneous power in ionization or excitation interactions. Obviously, the preservation of the time duration of the pulse is crucial for the success of the experiment.

The duration of an ultrafast pulse may be increased when it is subject to spectral dispersion with an ordinary diffraction grating. This is due to two major mechanisms. The first is the filtering of the pulse spectrum that occurs during monochromatization, which leads to a time broadening caused by the Fourier transformation of the spectrum. This effect is negligible for HH radiation if the complete spectral extension of a single harmonic is selected by the monochromator, so no modifications in its Fourier spectrum are induced.

The time stretching is mainly due to the difference in the lengths of the optical paths of the rays diffracted by different grating grooves. In fact, a single grating inevitably gives a time broadening of the ultrafast pulse because of the diffraction: the total difference in the optical paths of the rays diffracted by N grooves illuminated by radiation at wavelength λ is $Nm\lambda$, where m is the diffracted order. This effect is negligible for picosecond or longer pulses but is dramatic in the femtosecond time scale. Let us consider a 300 gr/mm grating illuminated on an area of 20 mm; the total number of grooves involved in the diffraction is 6000, corresponding to a maximum delay in the first diffracted order of 240 μm, i.e., 0.8 ps, at 40 nm. In case of a femtosecond pulse, this reduces dramatically both the time resolution capability and the peak intensity at the exit of the monochromator. Nevertheless, it is possible to design time-compensated spectroscopic configurations with gratings by using at least two gratings in a subtractive fashion to compensate for the dispersion [7]. In such a configuration, the second grating compensates for the time and spectral spread introduced by the first. There are two conditions that the design must comply with: the differences in the path lengths of rays with the same wavelength that are caused by the first grating must be compensated by the second grating, and two rays with different wavelengths within the spectrum of the pulse to be selected have to be focused on the same point (i.e., the global spectral dispersion of the monochromator has to be zero). Both these conditions are satisfied by a scheme with two equal concave gratings mounted with opposite diffraction orders: the incidence angle on the second grating is equal to the diffraction angle of the first grating. The spectral selection is performed by a slit placed in an intermediate position between the gratings, where the radiation is focused by the first grating. This design has proved to be very effective in the time compensation in the extreme-ultraviolet (EUV) for wavelengths longer than ≈ 40 nm, where normal-incidence configurations can be adopted. The main drawback of using two normal-incidence gratings in classical diffraction is the low efficiency in the EUV. By choosing a coating optimized for the EUV (gold, platinum, or

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iridium), the single-grating efficiency can be estimated to be ~ 0.1 and the global efficiency is ~ 0.01 or even lower.

The time compensation in the grazing-incidence region (below ≈ 35 nm) is harder because of the intrinsic difficulties of the grazing-incidence mountings that are highly sensitive to aberrations and misalignments: once the grating subtended angle has been chosen, the time compensation is optimum only in a narrow spectral region. In addition to this, the efficiency of grazing-incidence gratings is usually found to be lower than the normal-incidence case.

The HH spectral selection at short wavelengths is often done with multilayer optics, which nearly preserve the time structure because the bandwidth is high and only small path differences occur. Although a single multilayer mirror can be used for wavelengths lower than ≈ 30 nm to select a single harmonics with high efficiency, no multilayer optics are available at present for wavelengths longer than ≈ 40 nm. In addition, a tunable multilayer monochromator requires the use of different multilayer mirrors (one for each wavelength region to be selected) or the use of more complex optical configurations with two multilayer optics [8].

Here a grazing-incidence time-compensated monochromator with two gratings used in the conical diffraction mounting is presented. It can be used on a very large spectral region, ranging from EUV to soft X-rays, with effective time compensation and much higher efficiency than the classical diffraction mounting.

2 The conical diffraction mounting

The conical diffraction mounting differs from the classical one in that the incident and diffracted wave vectors are almost parallel to the grooves [9, 10]. In the case of using a blazed grating, the efficiency in conical diffraction is close to the reflectivity of the coating, so much higher efficiencies than the classical mounting are obtained in the EUV and soft X-ray region [11, 12].

The geometry of the conical diffraction is shown in Fig. 1. The direction of the incoming rays is described by two parameters, the altitude and the azimuth. The altitude γ is the angle between the direction of the incoming rays and the direction of the rulings. It defines the half-angle of the cone into which the light is diffracted: all the rays leave the grating at the same altitude angle at which they approach. The azimuth of the incoming rays α is defined to be zero if they lie in the plane perpendicular to the grating surface and parallel to the rulings, so $-\alpha$ is the azimuth of the zero-order light. Let β define the azimuth of the diffracted light at wavelength λ and order m. The grating equation can be written as

$$\sin\gamma(\sin\alpha + \sin\beta) = m\lambda\sigma, \qquad (1)$$

where σ is the groove density. The angle γ defines the cone of diffraction: different wavelengths are diffracted along an arc of a circle with radius equal to $L \sin\gamma$, where L is the distance covered by the light from the grating to the analysis plane perpendicular to the grating itself. The blaze condition is described as in the classical diffraction: the diffraction efficiency is maximized if the diffracted light is to leave the grating in such a way that it performs a specular reflection off the groove surface, that is, $\alpha + \beta = 2\delta$, where δ is the blaze angle of the grating. In addition, shadowing effects from adjacent grooves must be avoided to maximize the efficiency, that is, $\alpha = \delta$. The optimal performance of a blaze grating in conical diffraction is then achieved when $\alpha = \beta = \delta$, which means that the surface of each groove of the grating is seen by the incident ray as a plane mirror.

3 Time-compensated configuration

The schematic of the time-compensated monochromator is shown in Fig. 2. The two gratings are mounted in time-compensated configuration and subtractive dispersion. Both the conditions of the compensated monochromator design are satisfied: rays with the same wavelength cover the same path length in the monochromator, and rays with different wavelengths within the spectral region to be selected are focused at the exit on the same point.

The classical conical diffraction has been extensively studied with plane gratings illuminated in collimated light [13], but this requires the use of additional grazing-incidence mirrors for the focusing, increasing thereby the number of reflections and decreasing correspondingly the efficiency.

Aberration-corrected concave gratings are often used in EUV spectroscopy in the classical diffraction mounting to

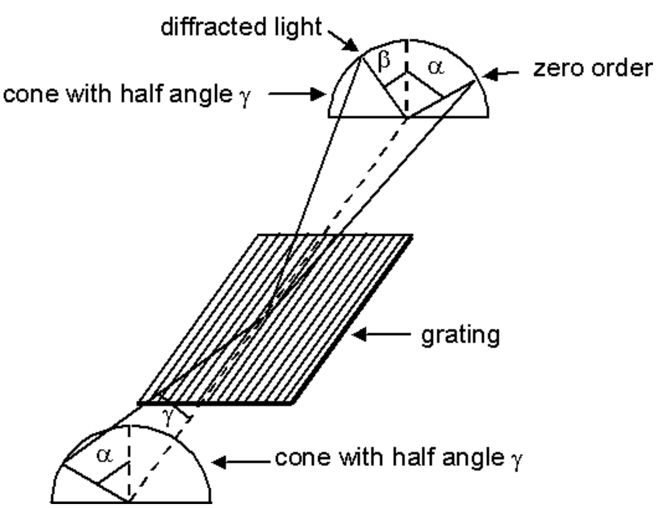

FIGURE 1 Conical diffraction mounting

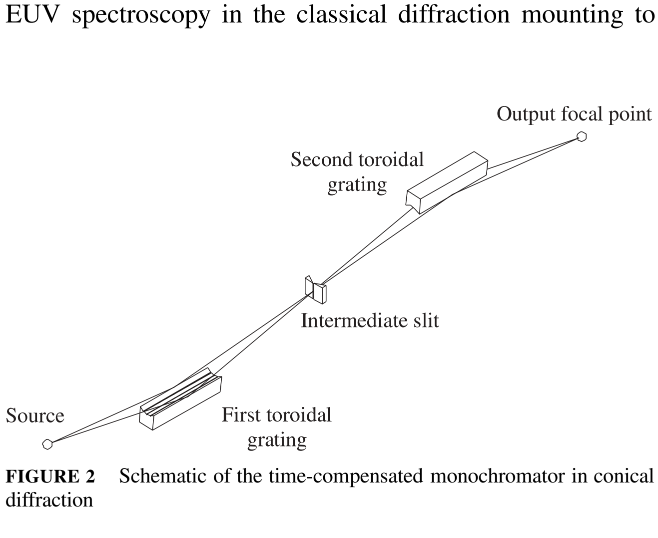

FIGURE 2 Schematic of the time-compensated monochromator in conical diffraction

minimize the number of optical elements and maximize the instrument throughput. The simplest such monochromator consists of a single optical element, namely, the grating, which provides both the spectral dispersion and the spatial reimaging of the entrance slit. Single-reflection designs with concave gratings give the highest efficiency, an extremely important consideration in the EUV spectral region, where reflectivity and diffraction efficiency for classical mountings are rather low.

The maximization of the efficiency is particularly important in the case of HH selection, due to the relatively faint emission from the HH source, so it is worthwhile to reduce the number of reflections to the minimum number of two, i.e., the two gratings necessary for the time compensation. To achieve this, every single grating has to provide both the spectral dispersion and the focusing, i.e., to be a so-called aberration-corrected grating. In this way, a polychromatic point source has to be imaged on the grating focal plane in several monochromatic points that are distinct because of the dispersion but separately focused because of the focusing properties of the optics. Since the gratings are working in grazing incidence, the focusing has to be performed by an optics with two substantially different radii in the tangential and sagittal plane: the simplest of such surfaces is the torus.

The configuration presented here has two gratings in conical diffraction that are toroidally bent in order to achieve spectral and spatial focusing with a single optics. The first grating creates a spectrally dispersed image of the source on an intermediate plane between the two gratings, where a slit carries out the spectral selection of the harmonics. Only a selected portion of the spectrum, i.e., a single harmonic or a set of a few harmonics, propagates through the slit toward the second grating, which compensates for the temporal delay introduced by the first grating and creates on the output plane a spectrally selected image of the source.

The wavelength scanning is performed by rotating the gratings around an axis tangent to their vertex and parallel to the grooves. The gratings are then operated at constant altitude angle γ and variable azimuth in the condition $\alpha = \beta$.

The characteristics of the monochromator are resumed in Table 1. The optical performances have been simulated by a ray-tracing program written in the laboratory for simulating EUV and soft X-ray optical systems and modified by the author to calculate also the length of the various ray trajectories, hence the temporal delay introduced by the configuration. The harmonics of a Ti : Sapphire laser with a fundamental wavelength of 800 nm are considered. The accepted aperture of the system is 10 mrad, which is larger than the measured harmonic divergence [14, 15]. Two couples of 200 gr/mm and 400 gr/mm toroidal gratings are used, respectively, for the 25–75 nm and 8–25 nm regions. The altitude angle is selected to be 4° to give still high reflectivity at the shortest wavelengths to be acquired.

The optical performances are resumed in Table 2. The use of toroidal surfaces is very effective in the correction of the aberrations. The full-width-at-half-maximum (FWHM) aberrations in the output plane are well confined below 20 μm.

The analysis of the time compensation is reported in Table 3. The spreads of the path lengths in a single harmonic, i.e., the difference in length between the longest ray and the shortest one, are reported both in the intermediate slit plane and at the exit. The differences in the path lengths are almost completely canceled by the compensated configuration. The residual mean time spread is estimated on the order of 1 fs.

Since the grazing-incidence reflectivity is much higher than the normal-incidence reflectivity and the diffraction ef-

Gratings	Toroidal
Groove density	200 grooves/mm (1–2) 400 grooves/mm (3–4)
Tangential radius	5730 mm
Sagittal radius	27.9 mm
Altitude angle γ	4.0°
Length of input and output grating arms	400 mm
Size	10 mm × 60 mm
Wavelength region	25–75 nm (1–2) 8–25 nm (3–4)
Total length of monochromator	1600 mm

TABLE 1 Characteristics of the monochromator

Gratings	Harmonic order	Δ_{SLIT} (μm)	Δ_{TOT} (μm)
1–2	H13	50.0	0.6
1–2	H15	41.4	0.3
1–2	H19	33.6	0.2
1–2	H31	20.7	0.2
3–4	H37	33.1	0.2
3–4	H61	20.6	0.2
3–4	H99	12.7	0.2

TABLE 3 Analysis of the compensation of optical path lengths for different harmonics. Δ_{SLIT} and Δ_{TOT} indicate, respectively, the spread of the path lengths in the intermediate slit plane after the first grating and at the exit

Gratings	Harmonic order	Azimuth $\alpha = \beta$ (deg)	AB_{SLIT} (μm)	AB_{OUT} (μm)	W_{SLIT} (mm)
1–2	H13 (61.5 nm)	5.0	20 × 12	16 × 12	1.2
1–2	H15 (53.3 nm)	4.4	16 × 11	10 × 6	1.0
1–2	H19 (42.1 nm)	3.5	14 × 10	8 × 8	0.5
1–2	H31 (25.8 nm)	2.1	11 × 10	12 × 16	0.2
3–4	H37 (21.6 nm)	3.5	10 × 14	10 × 8	0.25
3–4	H61 (13.1 nm)	2.1	10 × 11	17 × 12	0.10
3–4	H81 (9.9 nm)	1.6	11 × 10	20 × 15	0.05

TABLE 2 Optical performance of the time-compensated monochromator with toroidal gratings in conical diffraction. The source divergence is kept equal to 10 mrad. AB_{SLIT} and AB_{OUT} indicate, respectively, the FWHM aberrations in the slit plane and at the output. W_{SLIT} indicates the slit width to carry out the selection of a single harmonic (i.e., adjacent harmonics completely filtered out)

ficiency in conical diffraction is close to unity, the EUV efficiency of a grazing-incidence grating in conical diffraction is expected to be very high [11].

Some preliminary efficiency measurements in the 50–100 nm spectral region have been done at the beamline BEAR of the Elettra Synchrotron (Trieste, Italy) on a 600 gr/mm gold-coated plane blazed (7° blaze angle) grating manufactured by Richardson Gratings. The grating was operated in the same way as in the proposed time-compensated monochromator: the altitude angle γ is kept constant and, for a given wavelength, the azimuth angle α is selected following (1) in order to fulfill the condition $\alpha = \beta$. In this way, the blaze condition of maximum efficiency is satisfied only at wavelength λ_B for which $\alpha(\lambda_B) = \beta(\lambda_B) = \delta$ (δ is the blaze angle). At different wavelengths, the efficiency drops because the grating is operated slightly off-blaze. The tested grating was operated at 11.4° altitude angle. The measured efficiency in the first diffraction order is 0.55 at 80 nm (blaze wavelength) and decreases to 0.42 at 60 nm and 0.30 at 100 nm. These values are substantially higher than the normal-incidence efficiency of a grating in the conventional design. The results, while preliminary, are very encouraging in terms of realizing a high-efficiency instrument. A more complete set of measurements at BEAR is expected in the near future.

Despite the use of grazing-incidence optics, the time compensation is very effective in a broad band, ranging from EUV to soft X-rays, the wavelength scanning is simpler than the grazing-incidence classical mounting, and the global efficiency is much higher.

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