Laser and Particle Beams (2007), *25*, 391–396. Printed in the USA.

DOI: 10.1017/S0263034607000493

Realization of a time-compensated monochromator exploiting conical diffraction for few-femtosecond XUV pulses

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(RECEIVED 14 December 2006; ACCEPTED 2 May 2007)

Abstract

The general issue of the spectral selection of a portion of the wide extreme-ultraviolet spectrum obtained via extreme nonlinear processes as high order harmonic generation includes the problem of maintaining the ultrafast temporal duration of the pulses. In this paper, we present an instrument in which the pulse selection is operated in the wide wavelength range from 17 nm to above 60 nm, which is the central portion of the high-harmonics spectrum, with an instrumental function of about three femtoseconds. The design of the monochromator is based on the conical diffraction, which realizes very high diffraction efficiency by exploiting the specular reflection on the grating facets long-wise illuminated. The optical layout makes use of two gratings in the compensated-monochromator scheme already presented by the authors. The discussion of the residual aberration is also presented, with the aims to investigate the ultimate temporal resolution obtainable by this scheme.

Keywords: High harmonics generation; Ultra-short pulses; XUV-optics

1. INTRODUCTION

Research for novel mechanisms that generate pulses of electromagnetic radiation, of shorter and shorter duration, is naturally driven by the quest for ultrafast probe to investigate matter, and for the search for the mechanisms that induce novel coherent response to a laser pulse (Fürbach *et al.*, 2005, Isakov *et al.*, 2005, Kuroda *et al.*, 2005, Ozaki *et al.*, 2006). The actual frontier in the pulse shortness went over the femtosecond barrier a few years ago, with the generation of pulses in the extreme-ultraviolet (XUV) region, by means of the production of high-order harmonic (HH) of a short, and intense laser pulse (Agostini & DiMauro, 2004; Drescher & Krausz, 2005). Recently, the technique of the polarization gating, introduced more than a decade ago by Corkum *et al.* (1994), was successfully exploited to reach pulse's whose bandwidth may sustain duration shorter than the Bohr time, that is, the orbital period of the electron in the hydrogen atom, or 150 attoseconds (Sola *et al.*, 2006).

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Against these remarkable achievements, in the experimental techniques and in the physical understanding of the mechanism, for the ultrafast pulses' generation (Kapteyn & Brabec, 2006), the XUV optics deputized for the utilization of this radiation, and in particular, the monochromators that have to select a spectral portion, must be designed in order not to deteriorate the pulse's phase and then to cause a severe broadening of its duration. The broadband radiation source of reference when considering the pump-probe applications is the HHs field generated with few- or many-cycle pump pulse in the near infrared focused on a gaseous target (L'Huillier & Balcou, 1993; Chang *et al.*, 1997; Schnürer *et al.*, 1998; Nisoli *et al.*, 2003; Villoresi *et al.*, 2004). The solution to this optical problem has been proposed by Villoresi (1999, 2000) in terms of the so-called compensated monochromator and based on a two-grating design, and then developed by Nugent-Glandorf *et al.* (2002), Poletto (2004), Norin *et al.* (2004), Poletto *et al.* (2006), and Poletto and Villoresi (2006). The purpose of this paper is to describe the design and realization of an ultrafast monochromator of this type, the first realized using the conical mount of the gratings, and to discuss its performances and limitations. We will introduce in the next section, the concept of the compensated monochromator and the basics of its design. In Section 4, we will introduce the peculiarities of the conical diffraction for this case of application, and in the last section, we will describe the design of the actual monochromator. Presented also is the analysis of the optical path residual differences in the focal plane distribution. Finally, the experimental results obtained with the compensated monochromator realized in Laboratory.

2. THE COMPENSATED MONOCHROMATOR CONCEPT

The aims of the optical design of a time-compensated monochromator are, according to the above-described requirements, the selection of a portion of the spectrum of HH radiation. Its design prevent the negative effect of time broadening, which is introduced in the selection of a single harmonic, or a portion of it by a conventional dispersing type of instrument. The scheme of the monochromator is based on the use of at least two gratings in subtractive, and compensated dispersion, in order to realize two conditions: (1) for all the optical rays which propagate in the monochromator and which have the same wavelength, the differences in the optical-path lengths that are caused by the first grating have to be compensated by the second grating; (2) for two rays whose wavelength is within the selected spectrum of the pulse, they have to follow a path with the same optical length, and have to concentrate on the same focal point. Both these conditions are satisfied by a scheme with two equal concave gratings mounted with opposite diffraction orders (Villoresi, 1999, 2000). This scheme is demonstrated in Figure 1 in the case of the so-called normal incidence spectral region, and where the gratings adopt the Seya-Namioka mount to minimize defocus along the operative spectrum (Namioka, 1959). Three rays that hit the first grating and whose path length from the HHs source to the slit is different are shown in the figure. The reason for the path length different can be understood by studying the grating diffraction equation, that reads $d(\sin\alpha - \sin\beta) = m\lambda$, in which α is the incidence angle, and β is the diffraction angle, d is the grating pitch, and m is the diffraction order. In the example shown, the inequality $\alpha > \beta$ holds, the mount is said to be in the internal diffraction order $m = 1$, and the left-most rays has a shorter path. The paths of the other two increases in proportion to their separation from the hit point of the first ray s, positive going rightward, with a relation that depends on the actual wavelength λ:

$$\Delta l_{s-s} = \frac{ms\lambda}{d}, \tag{1}$$

where Δl_{s-s} is the variation in path length. The first grating is oriented to direct the spectral portion of interest in the direction of a slit, as in the usual case.

The correction of this Δl_{s-s} is the duty of the second grating, in which the diffraction order is the opposite, $m = -1$. In this grating, the rays hit with the same order than in the previous one, but now, according to Eq. (1), the variation of path length occur with opposite sign. Moreover, the combined dispersion of the two gratings is zero, since they are mounted in the subtractive dispersion. So all the spectral window selected by the slit is focused in the focus at the end of the monochromator.

At the same time, the optical aberrations have to be corrected in order not to introduce path length differences due to this cause. In the case of Figure 1, that is for normal incidence applications, the solution to this problem may be found by using a suitable toroidal design for the grating surface (Haber, 1950; Villoresi, 1999).

In the case of the radiation in the XUV spectral range, the choice of the optical components to be used in the design is limited to the reflecting surfaces. The use of the instruments for radiation, whose wavelength is shorter then 30 nm, further imposes the mount of the optical components in grazing incidence (Samson & Ederer, 1998). These constrains pose a serious difficulty in the design. In fact, all the major optical aberrations have a heavier effect, in this configuration, and, in order to meet the two conditions above, they are harder to correct in the spectral range of

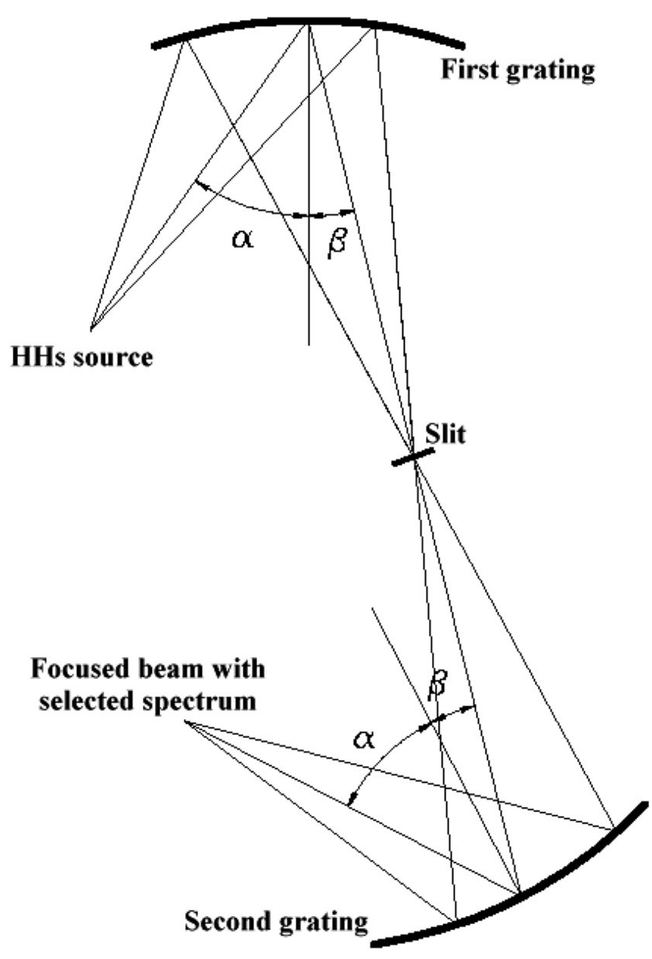

Fig. 1. Scheme of the compensated monochromator in the case of normal incidence spectral region.

operation. Moreover, the HHs radiation is generated via a mechanism whose efficiency is limited to about 10^{-3} and is usually much lower (Hergott *et al.*, 2002). Therefore, the throughput of the instrument has to be maximized, thus introducing the additional arduous requirement of very efficient design in the XUV range.

3. THE CONICAL DIFFRACTION

Taking into accounts these considerations, we have proposed the design of the compensated monochromator for the normal and grazing incidence spectral region on the base of the conical mounts of the gratings (Cash, 1982). In this case, the geometry of the incident and diffracted rays is that shown in Figure 2, in which the groove are almost parallel to the incidence plane and not orthogonal as in the ordinary diffraction.

The parameters that describe the rays' diffraction here are two, one more than for the ordinary: the altitude and the azimuth. The altitude γ is defined as the angle between the direction of the incoming rays and the direction of the grooves. This angle defines the half-cone in whose lateral surface, the diffracted ray will be directed according to the principle that all the rays leave the grating at the same altitude angle at which they approach. The other angle, the azimuth α and β, for the incident and diffracted rays, is the angle of the projection of the rays in the plane orthogonal to both the grating surface, and the groove direction made with respect to the grating normal. It is defined to be zero if the ray lies in the plane perpendicular to the grating surface and parallel to the rulings. Given the value α for the incident ray, $-\alpha$ is the azimuth of the zero order light, in specular reflection. The grating equation is written as

$$\sin\gamma(\sin\alpha - \sin\beta) = \frac{m\lambda}{d}. \tag{2}$$

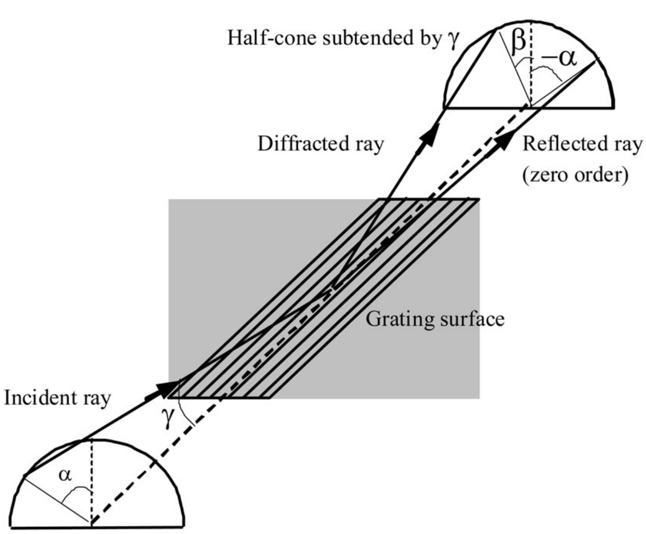

Fig. 2. Scheme of the conical diffraction mount of a plane grating.

The selection of the wavelength in the monochromator exit direction is operated by turning the grating around an axis parallel to the groove direction and passing through the grating centre. It results then that, for the conical diffraction, also the rotation is orthogonal to that of gratings in the ordinary mount.

In order to consider the maximum diffraction efficiency, the mount has to be done according to the blaze condition. This, similarly to the classical diffraction, is obtained when the grating facets, so to realize locally a specular reflection, reflect the rays secularly. This condition is obtained for

$$\alpha + \beta = 2\delta, \tag{3}$$

where δ is the blaze angle of the grating.

The efficiency is maximized when each grove is illuminated without shadow, which is when the incidence plane is parallel to the groove direction. This is realized by imposing the further condition

$$\alpha = \beta = \delta. \tag{4}$$

Under this condition, the equation for the diffraction becomes

$$2\sin\gamma\sin\delta = m\lambda\sigma. \tag{5}$$

According to the prediction of maximum efficiency, there was experiment verification in the XUV of the total efficiency of the grating in conical mount to be close to the reflectivity of the coating. This value is much higher than what measured in classical diffraction, (Neviere *et al.*, 1978; Werner & Visser, 1981; Cash, 1982; Pascolini *et al.*, 2006).

4. THE COMPENSATED MONOCHROMATOR USING THE CONICAL MOUNT

The design of the compensated monochromator that we realized was done by synthesizing the two grating scheme with the gratings in conical diffraction (Poletto, 2004). The correction of the optical aberration on a wavelength interval, which span about a decade (80-8 nm) forced the choice to divide the diffraction and the focusing of the rays. Therefore, unlikely the scheme of Figure 1, in which the grating is also focusing the incident radiation in the subsequent focal plane, we here adopted a design in which each section is composed of a collimator, the grating that diffracts a parallel beam and finally a focusing optics. The resulting scheme is shown in Figure 3. The collimators and the focusers were chosen to be toroidal mirrors. This component in fact shows fairly good properties in grazing incidence and is much simpler and cheap to realize than the parabolic mirrors, which, on the other hand, represents the exact solution to the finite-infinite conjugation problem.

https://doi.org/10.1017/S0263034607000493 Published online by Cambridge University Press

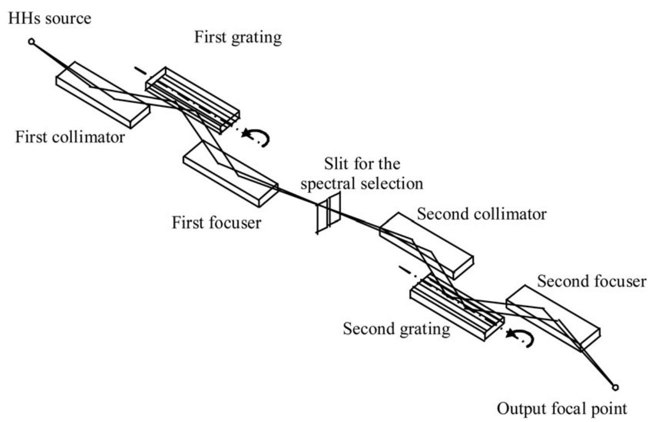

Fig. 3. Scheme of the 6-optics XUV grazing incidence compensated monochromator.

The gratings have plane surface, and they are operated in order to fulfill the blaze condition Eqs. (4) and (5). For the instrument that we have developed, they are ruled at 400 grooves/mm, with blaze angle $\delta = 6.5^\circ$ and are both operated at $\gamma = 3^\circ$.

The four mirrors' parameters are also mutually equal, and, for the case here studied, they have tangential radius $R = 11500$ mm and sagittal radius $\rho = 31.4$ mm. They are coated in platinum and are mounted at 87° of incidence, which assure a very good reflectivity in the XUV.

An example of the monochromatic image at the final focal plane is presented in Figure 4, in the case of a beam of maximum divergence 10 mrad at zero height, and for a point source at the wavelength of 30 nm. This value for the HHs divergence is typical for the radiation generated with few-cycle intense IR pulses (Nisoli *et al.*, 2002). The ray plot in Figure 4 demonstrates the correction of the aberrations for the six-optics monochromator to a very effective extent.

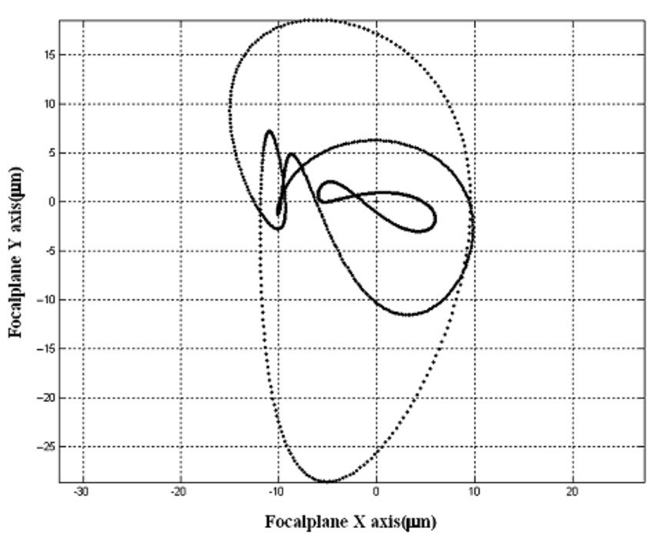

Fig. 4. Ray-tracing of the compensated monochromator calculated at the final focal plane. The chief-ray is at the origin.

In fact, from the figure it can be derived that the full spatial extension of the ray distribution is limited to a few tens of micrometers. From this example, it can be seen that the resulting distribution of the rays from an extended HHs source of typical diameter of several tens of micrometers is scarcely widened by the geometrical aberrations introduced by the optics.

The corresponding spread in the optical path length of the different rays has been calculated in the spectral interval of interest, and, for the point-like source of test. The root-mean-square value resulted always lower than half of a micrometer, from 20 up to 60 nm, and show the positive slope with lambda. This corresponds, in the time domain, to about 1.5 fs of rms spread of the XUV pulse at the output.

We present here, for the first time, the analysis of the spatial distribution of the path differences: Figure 5 shows the path length difference with respect to the chief ray, for the case of $\lambda = 30$ nm. In the figure, the value of excess path length with respect to the chief rays is indeed plotted relatively to the ray impact point on the focal plane. The resulting curves indicate this quantity for points that belong to three rings of equal emission angle with respect to the optical axis. It is evident that the spread is a strong rising function of the beam aperture, as seen for the increasing separation between the three curves, which correspond to semi-aperture of 1.6, 3.3, and 5 mrad, respectively. Moreover, the most evident deformation of these curves is the residual coma. This latter results from the deformation of the beam diffracted by the grating, that imposes an anamorphic rotation (Cash, 1982), and is zero at the specular reflection.

The instrument was realized in our Laboratory and the temporal characterization is presently under progress, while the image analysis and the efficiency assessment have already been realized. These measurements were done by using a laboratory hollow-cathode XUV lamp, acting as an extended source limited by an entrance pinhole of 100 μm of diameter.

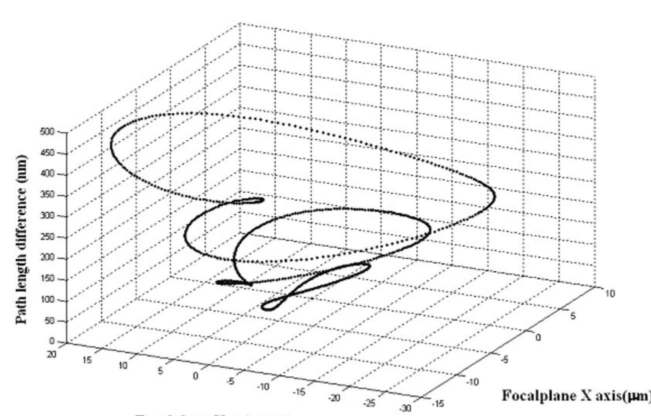

Fig. 5. Spatial distribution of the differences of the optical path length with respect to the chief ray. The total path for this latter is 1800 mm.

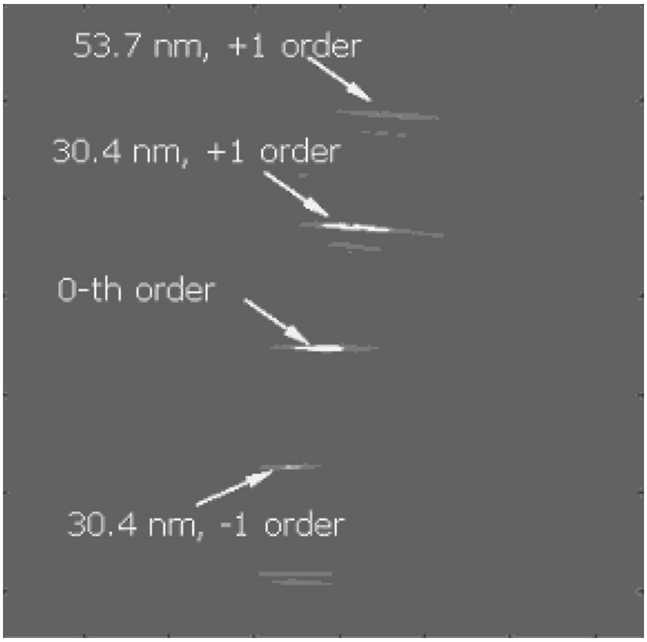

Fig. 6. Focal plane image obtained with He hollow cathode calibration lamp.

An example of the acquired spectrum that demonstrates the optical performance in agreement with the design is reported in Figure 6, in the case of the lower diffraction orders of the Helium emission. From the analysis of the line width size, which results of 100 μm, is it possible to ascertain the correct focusing properties of the monochromator.

The efficiency was also measured using the hollow-cathode lamp, with different gases. The peak efficiency of the complete system was found to be at or above 15% in the 25–35 nm intervals, and slowly decreasing for longer wavelengths. This result is significantly higher than the typical efficiencies shown by monochromators in classical diffraction.

In conclusion, we have reported on the design and realization of a compensated monochromator operating with the gratings in conical diffraction. The perspectives of its use are positively biased by the remarkably high efficiency demonstrated by the instrument, beside the good focusing properties and the wide spectral interval of operation.

ACKNOWLEDGMENTS

The authors would like to remember the contribution of Mr. Paolo Zambolin to the mechanical design of the different configurations and to thank Prof. Giuseppe Tondello for many useful discussions. This work has been partially supported in the framework of the SPARC FISR project funded by the Italian Ministry for University and Scientific Research.

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