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Time-delay compensated monochromator for the spectral selection of extreme-ultraviolet high-order laser harmonics

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The design and the characterization of a monochromator for the spectral selection of ultrashort high-order laser harmonics in the extreme ultraviolet are presented. The instrument adopts the double-grating configuration to preserve the length of the optical paths of different diffracted rays, without altering the extremely short duration of the pulse. The gratings are used in the off-plane mount to have high efficiency. The performances of the monochromator have been characterized in terms of spectral response, efficiency, photon flux, imaging properties, and temporal response. In particular, the temporal characterization of the harmonic pulses has been obtained using a cross-correlation method: Pulses as short as 8 fs have been measured at the output of the monochromators, confirming the effectiveness of the time-delay compensated configuration. © *2009 American Institute of Physics.* [doi:10.1063/1.3273964]

I. INTRODUCTION

The generation and utilization of high-order laser harmonics (HHs) have emerged in the past 2 decades as a new field of nonlinear optics with very attractive characteristics.[1] In fact, HHs produced by the interaction between a very intense ultrashort laser pulse and a gas jet represent an extreme-ultraviolet (XUV) radiation source with high brightness, coherence, and peak intensity. The HH spectrum is generally described as a sequence of peaks corresponding to the odd harmonics of the fundamental laser wavelength with an intensity distribution characterized by a plateau whose extension is related to the pulse intensity.[2] The use of advanced phase matching mechanisms and interaction geometries as well as intense ultrafast laser has been made possible to obtain HH radiation up to the water window region (2.3–4.4 nm) while still using as source a tabletop apparatus.[3] Moreover, due to the nature of the process, HH generation represents a powerful tool for temporal resolved measurements with subfemtosecond resolution.[4–8]

The characterization of processes involving the use of HHs deserves a particular attention in the design of the beamline that is demanded to manage the XUV radiation. Among the driving parameters, we can cite the need to operate in the single-shot mode, the sensitivity of the generation to both the laser parameters and the target conditions, the ultrafast temporal duration of the XUV pulses that must not be altered by the optical elements, the need to measure the absolute XUV photon flux. For various experiments the XUV pulse has to be focused onto a target, possibly in combination with a properly delayed and collinear visible or infrared (IR) pulse. In these cases, the suitable optical elements to manage the XUV radiation are grazing-incidence broadband concave mirrors that do not alter the temporal duration of the ultrashort pulses.[9]

Several applications require the use of single harmonics (or a group of few harmonics), which has to be extracted within the broad HH spectrum to obtain an ultrafast pulse at a suitable XUV wavelength to be scanned in a given range. The monochromator called for this purpose should also maintain the duration of the XUV pulse as short as in the generation process, to preserve the temporal resolution and the peak power. Such a monochromator can be generally modeled as a filter with a complex frequency response, $K(\omega)$, that includes both the nonuniform spectral transmission and the distortion in the spectral phase.[10] Since the XUV pulse may be generated with a temporal duration close to its transform limit, any modification of the spectrum results in a temporal broadening as described by the Fourier transform. In order to preserve the duration of the pulse at the output of the monochromator, the selected bandwidth has to be larger than the spectral width of the pulse; moreover, the transfer function $K(\omega)$ has to be almost constant within the bandwidth. Since harmonic peaks produced by multicycle femtosecond pulses are spectrally well separated, the first condition is verified if the monochromator selects the whole band of a single harmonic, so no modifications in the spectrum are induced. The second condition is almost always verified if the monochromator is realized by reflecting optics since the reflectivity variations within the linewidth of a single harmonic are usually negligible so that $K(\omega)$ can be considered constant, although lower than unity.

The most efficient way to select HHs with very modest temporal broadening is the use of a multilayer mirror in normal incidence, which does not alter the pulse duration up to

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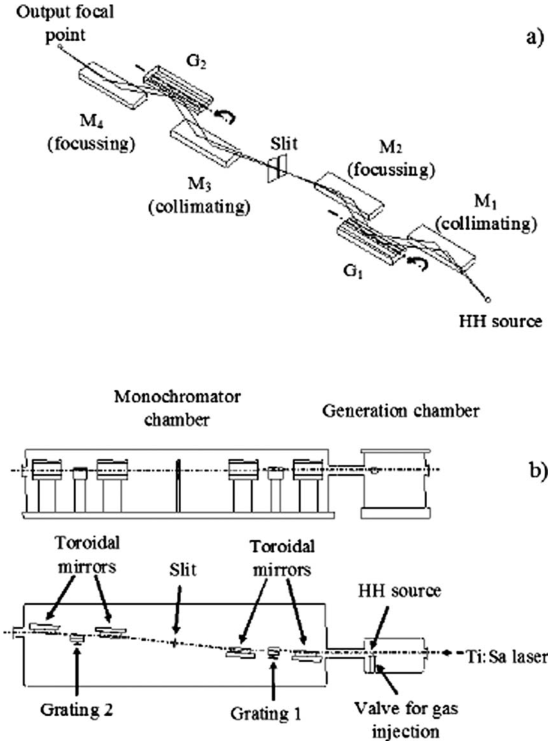

FIG. 2. Optical design (a) and schematic view of the TDCM (b).

TABLE I. Parameters of the toroidal mirror (a) and of the spherical variable-line-spaced (SVLS) grating (b).

(a) M_1 and M_4	
Surface	Toroidal
Tangential radius	18 000 mm
Sagittal radius	31.5 mm
Incidence angle	87.4°
Distance source-M_1	364 mm
Distance M_2-output	364 mm
Size	65×10 mm^2
(b) M_2 and M_3	
Surface	Toroidal
Tangential radius	14 000 mm
Sagittal radius	31.5 mm
Incidence angle	87.4°
Distance G_1-M_2	340 mm
Distance M_3-G_2	340 mm
Size	65×10 mm^2
(c) G_1 and G_2	
Surface	Plane
Groove density	400 lines/mm
Blaze angle	6.5°
Altitude	3°
Size	60×10 mm^2