Cubic phase distortion of single attosecond pulses being reflected on narrowband Mo/Si filtering mirrors

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Abstract: We show that cubic phase distortion caused by narrowband Mo/Si multilayer filtering X-ray mirrors may considerably increase the time duration of single attosecond pulses.

OCIS codes : (320.2250) Femtosecond phenomena; (340.7470) X-ray mirrors

1. Introduction

After reaching the sub-5 fs regime in the field of high power ultrashort laser pulse generation [1], an extended effort has been made in order to push the temporal resolution limit in the sub-femtosecond or attosecond (as) regime. Performing experiments on this timescale is extremely exciting: a many of fundamental physical processes, such as ultrafast electron dynamics, evolve in the sub-femtosecond regime. The possibility of generating attosecond pulses was predicted by Farkas and Tóth [2], and Antoine et al [3] by exploitation of high harmonic generation (HHG). High harmonics are typically generated in rare gases following the ionization process induced by high intensity lasers pulses and exhibit discrete frequencies that are the odd multiples of the original laser frequency. According to theory, selecting a proper range of these harmonics one can generate a train of attosecond pulses.

Single attosecond pulses can be obtained using a few cycle – about 5 fs – laser pulses for generation of a continuum in the soft x-ray spectrum, which continuum must be properly filtered by narrowband Si/Mo multilayer mirrors [4]. In order to obtain transform limited attosecond pulses, the intrinsic chirp of the continuum [5] should be compensated as well: chirped mirror structures developed for X-ray wavelengths [6] may solve this problem. An alternative approach has been recently proposed by Kim et al. [7] who used a thin Sn (Tin) layer for spectral filtering and compensation of the positive linear chirp of the continuum. This latter approach is limited by the fact that spectral filtering and dispersion compensation can not be independently adjusted.

In this paper we investigate phase properties of Mo/Si multilayer filtering mirrors developed for single attosecond pulse generation experiments [4]. We show that cubic phase distortion originating from narrow bandwidth ($\Delta E \approx$ 3 eV) Mo/Si multilayer filtering mirrors results in longer time duration and multiple pulsing. Interestingly, this effect reduces for higher bandwidth filtering mirrors, i.e., for shorter attosecond pulses.

2. Phase properties of Mo/Si multilayer filtering mirrors

Dispersive properties of thin film spectral filters such as Fabry-Perot thin film interferometers or reflective notch filters were discussed in Ref. [8]. In general, it was found that a rapid change in the spectral reflectivity/transmittance is accompanied by a rapid variation of the phase shift on reflection/transmission seriously harming femtosecond pulse operation.

For our studies in the 10 nm - 25 nm wavelength regime, which is typically used for single attosecond pulse generation [4], we used the multilayer Mo/Si filter designs presented in Ref. [9]: 30 bilayers of Mo and Si with spacing *d* of 9.1-9.5 nm with varying thickness ratios (Γ). In our calculation, Γ is defined as

$$\Gamma = \frac{d_{Abs}}{d_{Sp} + d_{Abs}}$$

in which equation d_{Abs} and d_{Sp} stand for the physical thickness values of absorbing Mo and the spacer Si layers, respectively. In our calculations, refractive index data listed in Ref. [10] were used. The computed spectral transmittance, reflectance and absorption of a multilayer Mo/Si filtering mirror with $\Gamma = 0.17$ is shown in Fig. 1a.

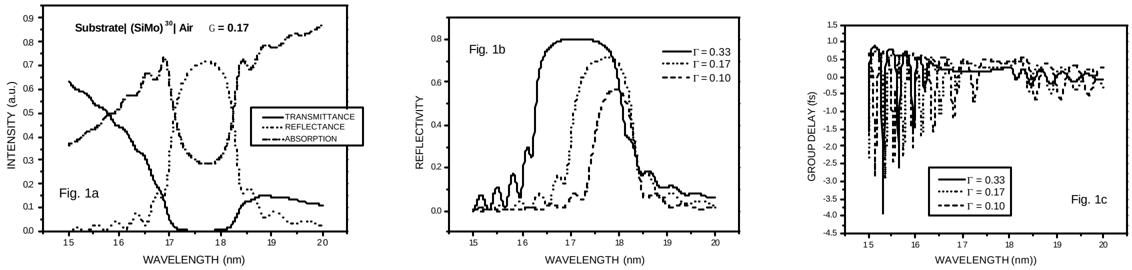

Fig. 1 Spectral transmittance, reflectance and absorption of a 30 bilayer Mo/Si filtering mirror with Γ value of 0.17 (Fig. 1 a), and spectral reflectance (Fig. 1b) and group delay (Fig. 1c) of such mirrors with different Γ values of 0.1, 0.17 and 0.33

One can observe that spectral transmittance and absorption exhibit a parabolic shape around the central wavelength of the filtering mirror. Since transmittance of the multilayer mirror is nearly zero in the 17-18 nm wavelength regime ($T(l) \approx 0$), the reflectivity vs. wavelength function $R(l)$ of the Mo/Si mirror is determined by the spectral absorption function $A(l)$ as follows:

$$R(l) \approx 1 - A(l)$$

In Ref. [11], we have pointed out that there is a strong relationship between reflection (absorption, scattering) losses and dispersive properties of multilayer dielectric mirrors: in general, losses on reflection are proportional to the group delay at wavelength l, in other words, expecting wavelength independent optical constants, the spectral absorption function $A(l)$ can be approximated as

$$A(l) \propto t(l)$$

In case of single attosecond pulse generation [4], the time duration of the pulse is determined by spectrum $I(l)$ and the spectral phase $j(l)$ of the frequency components. Exp ecting a continuum of uniform spectral intensity over the wavelength range of our interest, spectral intensity of the single attosecond pulse can be written as

$$I(l) \propto R(l),$$

while the spectral phase $j(l)$ is determined by the intrinsic linear chirp $j_{cont}(l)$ of the continuum and the (cubic) phase shift $j_{filter}(l)$ introduced by the Mo/Si filtering mirror: the first derivate of $j_{filter}(l)$ by the frequency is a quadratic function around the central wavelength of the filtering mirror:

$$t_{filter}(l) \propto 1-R(l)$$

By varying the thickness ratio between the absorber layer d_{Abs} and the spacer layer d_{Sp}, while keeping a fixed bilayer thickness of about 10 nm, one can change the high reflectivity bandwidth of the multilayer mirror [9] (see Fig. 1b). The corresponding (precisely) computed group delay versus wavelength functions are displayed in Fig. 1c. As we predicted, the shape of group delay vs. wavelength functions follow that of the corresponding spectral absorption functions. Interestingly, the group delay variation Δt over the reflectivity bandwidth of the mirrors does not depend on the Γ values, i.e., the cubic phase term reduces for higher bandwidth filtering mirrors.

3. Cubic phase distortion of single attosecond pulses reflected on multilayer Mo/Si filtering mirrors

Using the spectral reflectivity data $R(l)$ shown in Fig. 1b and the spectral phase data $j_{filter}(l)$ used for calculating the group delay functions shown in Fig. 1c, we can compute the temporal shapes of single attosecond pulses being spectrally filtered by Mo/Si filtering mirrors of different Γ values. The results of calculations are shown in Fig. 2.

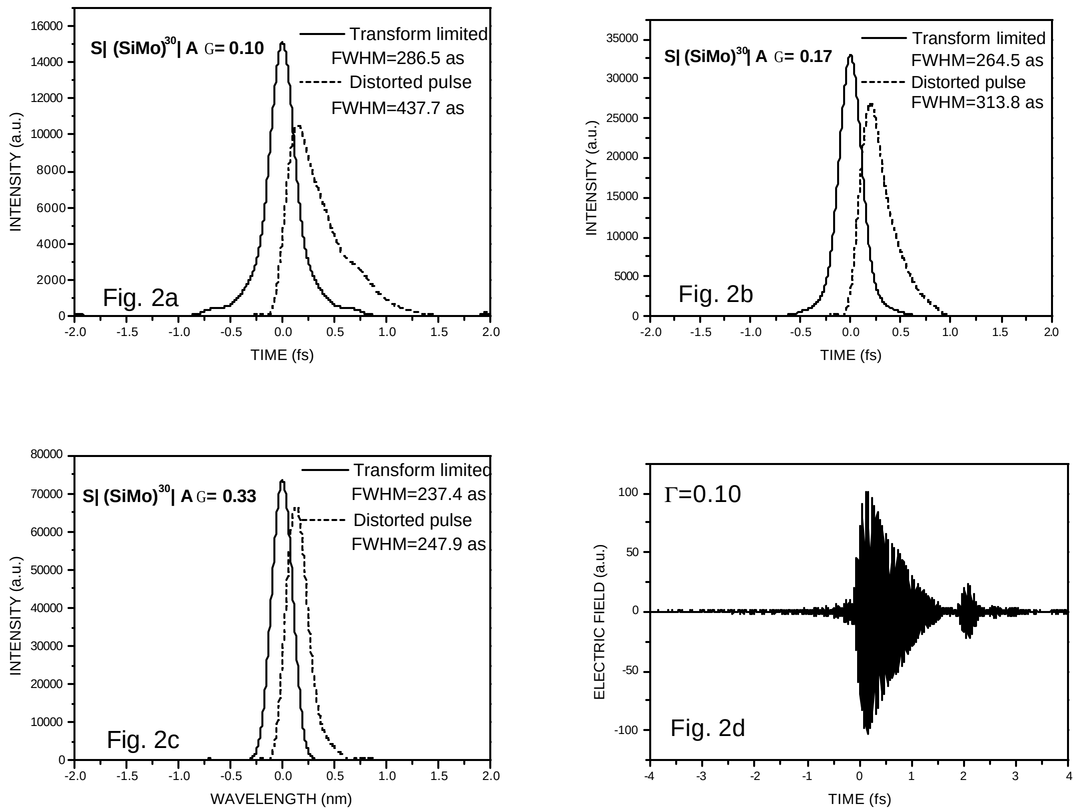

Fig. 2 The change of temporal pulse shape of single attosecond pulses being filtered by 30 bilayers of Mo/Si multilayer mirrors with Γ values of 0.1 (Fig. 2a), 0.17 (Fig. 2b) and 0.33 (Fig. 2c). The computed electric field of the attosecond pulse being reflected on the filtering mirror with Γ values of 0.1 is shown in Fig. 2d.

The most dramatic change in the pulse shape can be observed in the case of the filtering mirror with Γ value of 0.1: the pulse duration is increased from 286 as to 438 as (see Fig. 2a) due to the cubic phase and the pulse shape is strongly distorted (see Fig. 2d). This effect can be still recognized in the case of the Mo/Si multilayer mirror with Γ value of 0.17 (see Fig. 2b), when the pulse duration of the transform limited attosecond pulse is increased from 264 as to 314 as due to filter dispersion. In case of the highest Γ value (and highest bandwidth!), the effect of cubic phase can be neglected: this filter supports nearly transform limited pulse durations below 250 as (see Fig. 2c).

4. References

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