Design of chirped Mo/Si multilayer mirror in the extreme ultraviolet region

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The chirped Mo/Si multilayer mirror in the extreme ultraviolet region is designed to obtain sub-femtosecond pulses from high-order harmonics. Numerical simulations of temporal profile of the pulses are made for superposition of incident high-order harmonics and that of reflected ones by the chirped multilayer mirror. The normal incidence reflectivity and chirp in the wavelength range of $12.5-16.5$ nm are $6.7\% \pm 0.5\%$ and -3617 ± 171 as^2, respectively. Simulation results indicate that the designed chirped multilayer mirror can be used for producing 104-as pulses.

OCIS codes: 320.1590, 260.7200, 230.4170.

A major effort in ultrashort and ultrafast optics in recent years is to produce sub-femtosecond pulses. The study of time-resolved dynamics of electrons[1] has come true with the emergence of sub-femtosecond pulses[2]. High-order harmonics are generated when an intense short-pulse laser is focused into a jet of rare gases. Theory and experiments have demonstrated that sub-femtosecond pulses can be produced by superposing several high-order harmonics in the extreme ultraviolet region[3−6]. But high-order harmonics have an intrinsic chirp[7], resulting in the pulses broadening. Femtosecond pulses can be obtained by using the chirped multilayer mirror in the visible and near infrared region[8−10], and sub-femtosecond pulses can be obtained in the extreme ultraviolet region[11,12]. But nearly all the materials have the effect of absorption in the extreme ultraviolet region, and the trade-off between the high reflectivity and the chirped compensation in a broad wavelength range should be considered to obtain sub-femtosecond pulses, so it is difficult to design a practical chirped multilayer mirror. Genetic algorithm provides an effective tool for solving the problem. In this letter, a chirped multilayer mirror in the extreme ultraviolet region was designed using the genetic algorithm. Its capability of producing sub-femtosecond pulses was verified by numerical simulation.

Genetic algorithm is a powerful optimization method inspired by biological selection and genetic evolution. The procedure of designing the multilayer using this algorithm is as follows. Firstly, a computer generates a population of initial data randomly, which is equivalent to a population of multilayer thicknesses. Secondly, the operators of selection, crossover and mutation are applied to get better designs[13] evaluated by merited function. If the value of merited function is smaller than the target value or the loop times are larger than the presetting numbers, the termination criteria will be satisfied. The designing program was computed with our codes based on Fortran language.

The theoretical chirp of high-order harmonics for a neon atom exposed to an 800-nm wavelength radiation with intensity of 6.0×10^{14} W/cm^2 was calculated using the semiclassical three-step model[7]. The chirp is nearly constant from harmonic 35 to harmonic 75 (H35 to H75, corresponding to the wavelength range of $10.7-22.9$ nm), which is 3600 as^2. Considering the material selection and the optimization difficulty, the wavelength range of the normal incidence chirped multilayer mirror was chosen as $12.5-16.5$ nm, which includes eight high-order harmonics from H49 to H63. The Mo/Si material pair was selected, which gives high reflectivity in the wavelength region around 13 nm. The optical constants of molybdenum and silicon are available from the Center for X-Ray Optics at Lawrence Berkeley National Laboratory, USA[14]. The dependence of the reflectivity of the normal incidence Mo/Si periodic multilayer on the increment of the number of layers at different wavelengths is shown in Fig. 1. It can be seen that the reflectivity tends to be saturated with the increment of the number of layers, so the number of layers of 50 was chosen while designing the chirped multilayer mirror. To account for technological constraints, the layer thickness was limited in the range of $1-5$ nm.

In addition, the merited function F was chosen as

$$F = k_1 \sum_{i=1}^{n} (R_i - R_0)^2 + k_2 \sum_{i=1}^{n} (C_i - C_0)^2, \qquad (1)$$

where n is the wavelength point number in the designed wavelength range, R_0 and C_0 are the target reflectivity

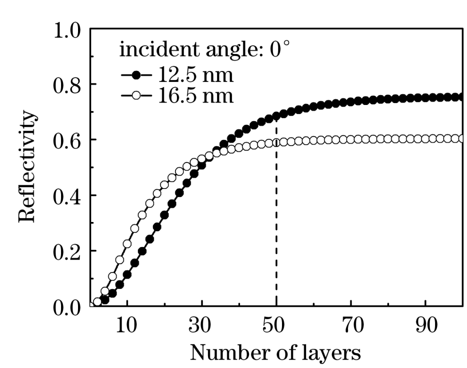

Fig. 1. Reflectivity of the Mo/Si periodic multilayer at normal incidence versus number of layers at different wavelengths.

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and chirp, respectively, R_i and C_i are the calculated reflectivity and chirp, respectively, and k_1 and k_2 are the weight factors. Reflectivity was calculated by Fresnel reflection coefficient method[15], and chirp was expressed by[7]

$$C = \frac{\partial^2 \phi}{\partial \omega^2}, \tag{2}$$

where ϕ is the phase of the multilayer, ω is the angular frequency of the incident light. C_0 was set as -3600 as^2 for eliminating the positive chirp of high-order harmonics, and R_0 was chosen as 7% after several calculation tests.

The reflectivity and the phase of the designed chirp multilayer mirror are shown in Fig. 2 and the chirp is shown in Fig. 3. The reflectivity and the chirp are $6.7\% \pm 0.5\%$ and -3617 ± 171 as^2, respectively. The phase shown in Fig. 2 seems linear due to a small chirp, but varies nonlinearly in the designed wavelength range. The thickness of each layer of the designed chirped multilayer mirror is given in Fig. 4. The layer at the vacuum boundary is silicon, and the layer at the substrate boundary is molybdenum.

In addition, we reconstructed the pulses by using the method described in Refs. $[4-6, 8]$ so as to verify its capability to produce sub-femtosecond pulses. The high-order harmonics from H35 to H75 were considered in the numerical simulation for better comparison between the direct superposition and the mirror's reflection. Since the spectra of high-order harmonics present a broad plateau of almost constant conversion efficiency[3], the amplitudes of high-order harmonics in numerical simulation were assumed to be 1, and the results are shown in

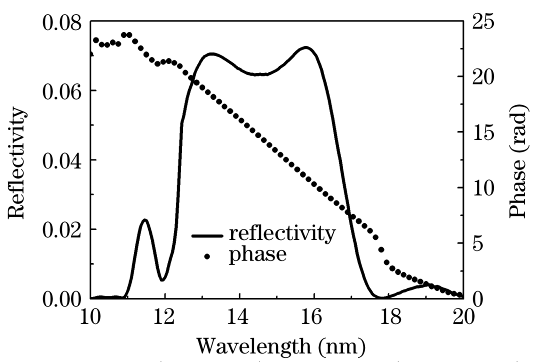

Fig. 2. Reflectivity (solid line) and phase (dotted line) of the designed chirped Mo/Si multilayer mirror.

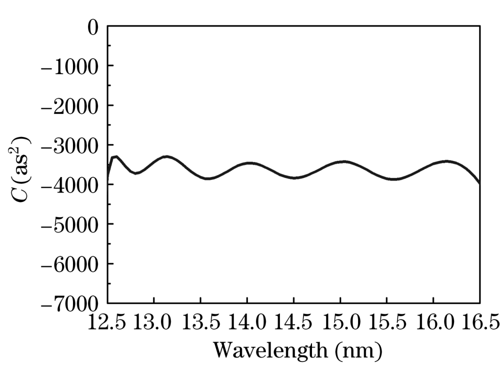

Fig. 3. Chirp curve of the designed chirped Mo/Si multilayer mirror.

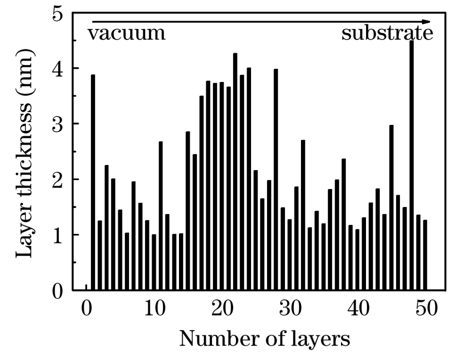

Fig. 4. Thickness of layers in the designed chirped Mo/Si multilayer mirror.

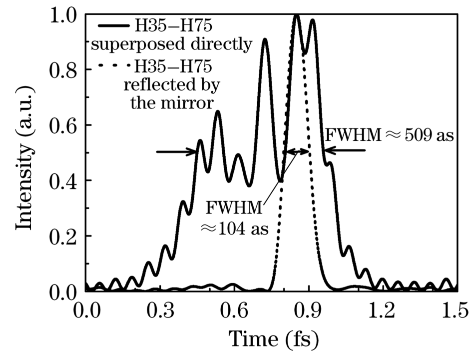

Fig. 5. Temporal profiles of H35—H75 high-order harmonics superposed directly (solid line) and superposed after reflected by the chirped Mo/Si multilayer mirror (dashed line).

Fig. 5. The pulses were normalized in intensity and centered in time for easier comparison. The pulse duration is compressed from 509 to 104 as by the designed chirped multilayer mirror. Before fabrication, thickness error and roughness should be considered. Calculation results show that the thickness error of ± 0.2 nm would cause the reflectivity and the chirp to decrease by about 7% and 9%, respectively. Assuming a roughness of 0.5 nm, the reflectivity is decreased to $5.5\% \pm 0.5\%$, while the chirp is -3635 ± 206 as^2.

In summary, the genetic algorithm has been used to design the chirped multilayer mirror in the extreme ultraviolet region. The capability of producing sub-femtosecond pulses of the designed chirped multilayer mirror has been demonstrated by numerical simulation. Simulation results indicate that the designed chirped multilayer mirror can be used for production of 104-as pulses.

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