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Metrologies for the Phase Characterization of Attosecond EUV Optics

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EUV optics play a key role in attosecond science since only with higher photon energies is it possible to achieve the wide spectral bandwidth required for ultrashort pulses. Multilayer EUV mirrors have been proposed and are being developed to temporally shape (compress) attosecond pulses. To fully characterize a multilayer optic for pulse applications requires not only knowledge of the reflectivity, as a function of photon energy, but also the reflected phase of the mirror. This work develops the metrologies to determine the reflected phase of an EUV multilayer mirror using the photoelectric effect. The proposed method allows one to determine the optic's impulse response and hence its pulse characteristics.

OCIS codes: 120.5050, 340.7470, 320.1590, 340.7480.

The development of high harmonic generating (HHG) sources has created a probe for the attosecond world in the extreme ultraviolet (EUV) spectrum [1,2]. Producing attosecond light pulses requires a light source with a large bandwidth. The minimum full width at half max (FWHM) bandwidth for a Gaussian pulse is described by the Fourier transform theory relation between the time domain and the frequency/energy domain:

$$\Delta\tau \cdot \Delta E \geq 1.8 \tag{1}$$

where $\Delta\tau$ is the length of the pulse in fs units and ΔE is the FWHM bandwidth in eV units. For a Δt = 100 attosecond pulse this means that the minimum FWHM reflectivity bandwidth ΔE for the optic is 18 eV. Large bandwidth is not the only requirement to make an ultrashort pulse. To obtain the minimum pulse width there is a requirement on the alignment of the phases of every frequency in the pulse. More specifically the second order term in a Taylor expansion of the phase, with respect to frequency, must be zero:

$$\varphi = \varphi(\omega_{cent}) + \varphi'(\omega_{cent})(\omega - \omega_{cent}) + \varphi''(\omega_{cent})(\omega - \omega_{cent})^2 / 2! + \Lambda \tag{2}$$

Where φ is the phase, $\varphi(\omega_{cent})$ is a constant called the carrier envelope phase, $\varphi'(\omega_{cent})$ is the first derivative of the phase called the group delay, and $\varphi''(\omega_{cent})$ is the second derivative of the phase and is called the group delay dispersion. The term called the group delay dispersion (GDD) or chirp of the pulse adversely effects the pulse size [3] by:

$$\tau = \tau_0 \sqrt{1 + \frac{16(\ln 2)^2 \{\varphi''(\omega_{cent})\}^2}{\tau_0^4}}\ . \tag{3}$$

Where τ is the pulse size, τ_0 is the delimited pulse size from purely bandwidth requirements, and $\varphi''(\omega_{cent})$ is the GDD evaluated at the central frequency ω_{cent} of the pulse's bandwidth.

EUV multilayer optics have been proposed and implemented as focusing elements for these attosecond HHG pulses [4]. They have also been proposed to compensate for the intrinsic chirp in the HHG systems [5]. However no straightforward method has been available to determine the reflected phase of the multilayer as compared to the incident phase. Our research has developed and implemented a simple method to measure the reflected phase of an EUV multilayer mirror using measurements of the total electron yield (TEY) to probe the standing wave at the mirror surface.

Traditional methods for measuring the reflective phase of an optic use interferometric techniques [3]. However, in the EUV these techniques are limited often to grazing incidence or a narrow bandwidth due to the use of a multilayer beamsplitter for normal incidence measurements. Either way, these techniques are difficult to apply due to the stringent constraints, which scale according to wavelength, on position accuracy to obtain the optical phase. As position accuracy of a fraction of the wavelength is often required, in the EUV this translates to a few nm in position accuracy and vibration stability.

The technique investigated here uses TEY along with reflectivity measurements to probe the standing wave at the surface of a multilayer film. The TEY is proportional to the intensity of the standing wave field at the surface of a thin film [6]. Multilayer thin films work on the principle of temporal coherence, in other words the reflected wave is coherent with respect to the incident wave at the top surface.

$$TEY = C(\omega)\cdot I(\omega)$$
$$I = \left|E^2\right| = \left|\left(E_{inc} + E_{ref}\right)^2\right| = \left|E_0^2\left(1 + r\cdot e^{i\Delta\varphi}\right)^2\right| = E_0^2\left(1 + r^2 + 2r\cos(\Delta\varphi)\right) \tag{4}$$

Where C carries the material dependence of the total electron yeild, E_0^2 is the incident field, r^2 is the wavelength dependent reflection coefficient and $\Delta\varphi$ is the difference in phase between the incident wave and the reflected wave. This analysis becomes slightly more complicated due to the non-zero escape depth of electrons, however correction factors for this effect can be taken into account [7].

In order to test the method, two different quadratically depth-graded Mo/Si multilayers and one periodic Mo/Si multilayer were produced. The multilayers were designed to be used at 10° from normal incidence, at a central wavelength between 13 to 14 nm, and have average GDD values of 0.0956, -0.0488, and -0.0001 fs^2. Realistic simulations of these multilayer stacks that included interdiffusion [8,9] and experimentally verified optical constants [10, 11, 12] were used as comparison to the measured data. TEY and reflectivity measurements were preformed at ALS beamline 6.3.2 [13] which is designed for EUV optical metrology and reflectivity measurements. The beamline has high spectral purity, and a spectral resolving power (eV/ΔeV) of up to 7000, a wavelength accuracy of 10^{-3} nm, and a reflectivity accuracy of 0.1% (absolute). The reflectivity measurements are shown in Figure 1. The TEY data, shown in Figure2, were collected using a Keithley 428 current amplifier and a collection voltage of 20V. At 20V the current reached 99% of saturation and the current became virtually independent of the applied voltage. This produced noise levels and repeatability of less than ± 2%. The measured TEY from a 10 nm thick sputtered Si film was used to normalize out the material dependence C(ω) in eq. (4) The data were also normalized to the ALS storage ring current to account for the different incident field intensity E_0^2 used for the measurements.

The phase calculated from the measured reflectivity and normalized TEY is shown in Figure 3. Inverting equation 4 retrieved the difference in reflected phase from the incident phase:

$$\Delta\varphi = \pm\cos^{-1}\left(\frac{J - R - 1}{2\sqrt{R}}\right) + 2\pi n \tag{5}$$

Where J is the normalized photocurrent, R is the square of the reflection coefficient (reflectivity), and n is an integer. As the arccosine function is multivalued, the choice of n and the sign of the arccosine were taken to make $\Delta\varphi$ continuous and initialized to have the highest photon energy measured to fall between 0 and π.

It would be difficult to use the second derivative of discrete experimental phase data points to determine the average GDD, because they would appear very noisy. Instead we fit a quadratic polynomial function to the phase and took the second derivative of the polynomial to determine the average GDD. A polynomial fit was chosen to allow the GDD to match the definition given in equation 2. The GDD of the three samples was determined to be 0.0962, -0.0439, and 0.00476 fs^2, which is in good agreement with the desired delays.

A simple method has been developed to measure the reflected phase of a multilayer with respect to photon energy. This method utilizes the interference on the surface of the optic and the total electron yield off the optic to determine the phase. Combining the phase measurement with the reflectivity measurement allows one to determine the impulse response and GDD of EUV optics for pulse applications.

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Figure Caption 1: Three samples were produced for this experiment; two quadratic depth-graded or chirped samples and one periodic sample. The two quadratic graded samples were designed to have opposite signs for their group delay dispersion (GDD) and the positive GDD sample was designed to have twice the chirp compared to the negative GDD sample. Plotted are the measured reflectivity curves for the three samples (points as indicated in the inset) and their simulations (solid lines). The samples are labeled by their GDD.

Figure Caption 2: The normalized total electron yield (TEY) measurement is shown for the positive GDD sample plotted as ▲. The normalization is such that a value of 1 would correspond to the TEY value of sputtered Si. Plotted along the same graph, as a line, is the simulated intensity of the surface electric field based on the reflectivity and the reflected phase.

Figure Caption 3: The phase for the three samples was reconstructed from the reflectivity and TEY data. Plotted as solid lines is the calculated phase of the multilayers.

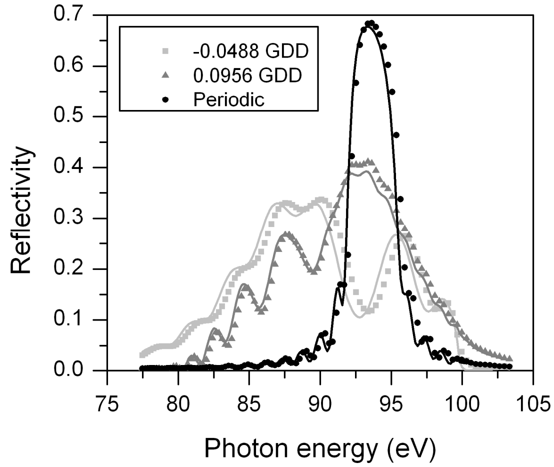


Figure 1

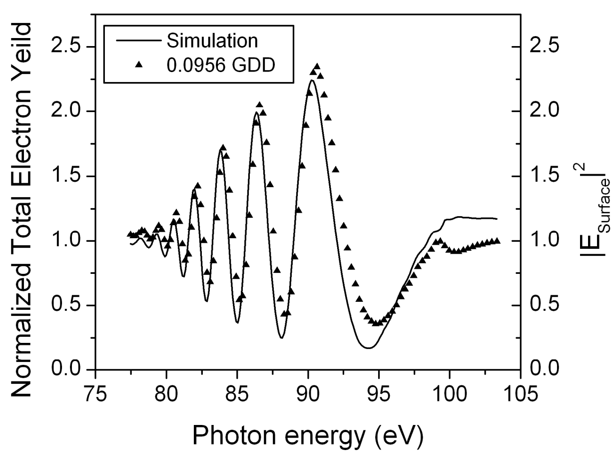
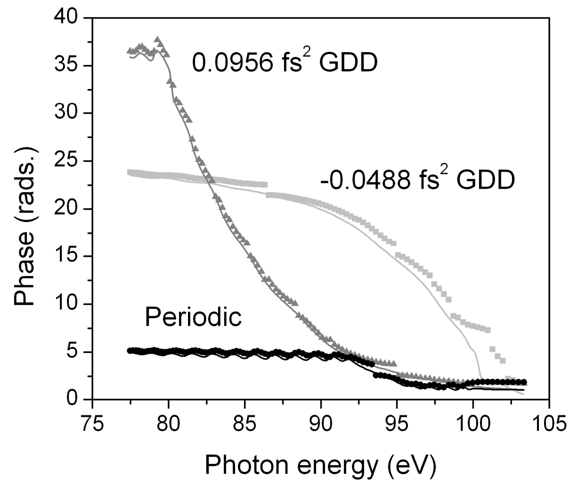


Figure 2



0.0956 fs^2 GDD
-0.0488 fs^2 GDD
Periodic
Phase (rads.)
Photon energy (eV)
0
5
10
15
20
25
30
35
40
75
80
85
90
95
100
105

Figure 3