Investigating the interaction of x-ray free electron laser radiation with optical materials


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The challenging properties of XUV and soft X-ray Free Electron Laser (FEL) radiation (intensity, pulse duration, coherence…) put highly demanding constraints on the design of optical components. The development of FEL beamlines relies on the knowledge of damage thresholds for optical elements (defined as any kind of modification of the optical properties), but these are nowadays largely unknown in the x-ray domain. The experiment was dedicated to determine the damage threshold of several materials of interest for optical elements ranging from mirrors coating and multilayers (amorphous carbon, B₄C, Au, W, Pt, Mo, Ni), scintillators (diamond, ZnO, Ce:YAG) to materials that can be used for beam stopper (bulk B₄C, graphite). The sample were placed, under vacuum, in the focus of a 2 m focal length mirror. The pulse duration was in the 80-150 fs range, and the radiation wavelength was measured to be 4.6 ± 0.1 nm. As an example of the results obtained, we present the specific case of damage mechanism on grating [1].

The 200 l/mm (5 µm periods) grating sample was produced by ion etching of a 1 mm thick Si wafer, with a duty ratio of 0.4. The groove depth was measured to be 13.5 nm. The etched wafer was then coated with 45 nm of amorphous carbon (a-C), which is a typical coating for XFEL optics. Atomic force microscopy (AFM) measurement confirms that the coating exactly reproduces the ion etched profile. The grating sample, as well as a mirror-like flat sample also made of 45 nm thick a-C coated on Si substrate, was exposed to single pulses with varying pulse energy. The beam was impinging the sample at the grazing angle 2° ± 0.1, following a procedure described in [2].
The exposed samples were analyzed ex-situ by optical differential interference contrast (DIC) microscopy which is sensitive to variations of optical refractive index, hence to any phase change, evidenced by a change of color. For both flat and grating sample, the energy damage threshold (E_{th}) was determined by plotting the damaged area versus pulse energy. A line fit through the point gives a threshold for grating E^{G}_{th} = 0.40 ± 0.04 µJ and E^{M}_{th} = 1.17 ± 0.16 µJ for the flat sample. The error bars corresponds to the confidence on the fit, at the 4.60 nm wavelength. We then calculate the ratio E^{M}_{th} / E^{G}_{th} = 2.92 ± 0.69, which is independent of the beamline transmission value. The damage fluence threshold (F_{th}) is retrieved from the values of E_{th}. The effective area at normal incidence is found to be A_{eff} = 22 ± 2 μm². We assumed that beam footprint in case of grazing incidence is equal to the projected area, e.g. A_{eff} / sin (2). We obtained: F^{G}_{th} = 63.7 ± 8.7 mJ / cm² for the grating and F^{M}_{th} = 186.6 ± 29.9 mJ / cm² for the flat sample. A specific feature of the damage mechanism can be observed in the left part of Figure 1. The measurements obtained with DIC microscopy, show the onset of the damage on the edge of the grating structure. The AFM measurements confirm this observation, and show the extension of the damage first on the top of the groove as the fluence is increasing.

To gain deeper insight in the understanding of the beam / grating interaction, an accurate model has to be used. In fact, the electric field distribution at the surface of a grating can be highly non-homogeneous, especially while dealing with a coherent laser beam. We simulated the deposited energy distribution in the grating by solving the Helmholtz equation in a paraxial approximation. The x-ray intensity distribution of the electric field is shown in left part of Figure 1. A standing wave builds up close to the grating’s surface. The inset in Figure 1 depicts the distribution of the absorbed energy in the grating’s structure. The maximum absorption is taking place at the edge of the grating structure where the onset of damage is experimentally observed. Moreover, similar simulations (not shown) were also performed with a mirror-like flat surface. The ratio of the maximum energy absorbed in the grating to the absorbed energy in the flat mirror is found to be 3.37, value which can be directly related to the ratio of the damage thresholds. Both values agree, within the error bar of the experiment, demonstrating the quantitative accuracy of our approach.

References