EUV Research at Berkeley Lab: Enabling Technologies and Applications

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Abstract The tremendous progress in the development and deployment of lab scale extreme ultraviolet (EUV) sources over the past decade has opened up the door to a wide variety of new users beyond the traditional synchrotron community. The practical use of such sources, however, is heavily dependent on the availability of EUV optical components. In this manuscript, we describe recent advances at Berkeley Lab in the development of reflective and diffractive optical structures for imaging, wavefront encoding, metrology, spectral filtering, and more.

1 Introduction

Advances in high harmonic generation (HHG) and extreme ultraviolet (EUV) laser sources [1–4] have enabled the spread of coherent EUV applications beyond synchrotrons. Such applications often rely on the availability of specialized EUV optical components such as multilayer mirrors and diffractive optics. Although such components have been developed over the years for synchrotron use, specific application to lab-scale sources has driven new developments. Here we provide an overview of some of these developments including in the area of broadband optics, spectral filtering optics, and high efficiency zoneplates. We also describe an EUV microscopy application making use of such components with an HHG source.

2 Multilayer Optics

A key enabling technology for EUV optics is the multilayer coating [5], [6]. In addition to serving as high efficiency mirrors, multilayers can also act as spectral filters. For example when using HHG sources with diffractive optics, it may be necessary

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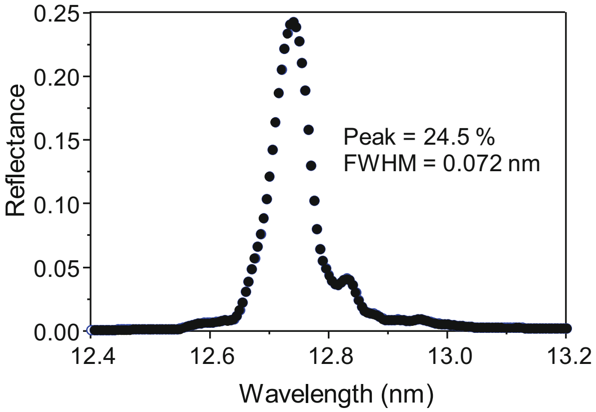

Fig. 1 Reflectance of line-narrowing multilayer achieving $\lambda/\Delta\lambda$ of 175

to narrow the intrinsic bandwidth of the source. The relative bandwidth reported in the literature [7] from high efficiency HHG sources is typically in the 50–100 range significantly restricting the number of zones one can use in the zoneplate. Figure 1 shows the results from the development of a line narrowing multilayer. The mirror is designed for a centroid wavelength of 12.7 nm and an angle of incidence of 6°. The mirror achieved a relative bandwidth ($\lambda/\Delta\lambda$)of 175 and peak reflectance of 24.5 % representing a bandwidth reduction of approximately 10 × compared to a conventional multilayer mirror with a loss in reflectivity of only about 2.6 × . The Mo/Si mirror was fabricated using magnetron sputtering and is comprised of 300 bilayers and has a gamma (ratio of Mo thickness to bilayer thickness) of 0.125. The measurements in Fig. 1, as well as all subsequently reported multilayer measurements, were performed using the Center for X-ray Optics Calibrations and Standards beamline at the Advanced Light Source synchrotron facility.

Even when the intrinsic bandwidth of a single harmonic is suitable, the use of HHG source may require the extraction of a specific harmonic. Multilayers can also be designed for this purpose by achieving the optimal balance between reflecting the target harmonic and suppressing adjacent harmonics. To this end, we attempt to place harmonic at nulls in the multilayer wavelength-dependent reflectance. Figure 2 shows the reflectance curve for such a mirror which was also specified to be a approximately 45° turning mirror. The locations of the harmonics are shown as red dashed lines in the plot. The mirror has a peak reflectivity of 42 %.

When working with ultrashort (broadband) pulses, it may in fact be required to have extended bandwidth multilayers to preserve the pulse width. This however will come at the cost of reflectivity. Figure 3 shows a broadband Mo/Si mirror designed for near 14-nm operation and achieving a reflectivity of approximately 20 % with a bandwidth of 3 nm. The Mo/Si mirror is comprised of 100 layers total in an aperiodic configuration determined using a model based optimization process [8].

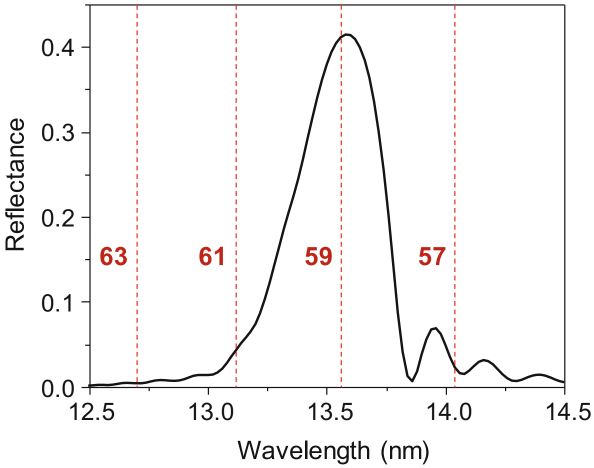

Fig. 2 Reflectance of harmonic selecting multilayer achieving peak reflectivity of 42 %

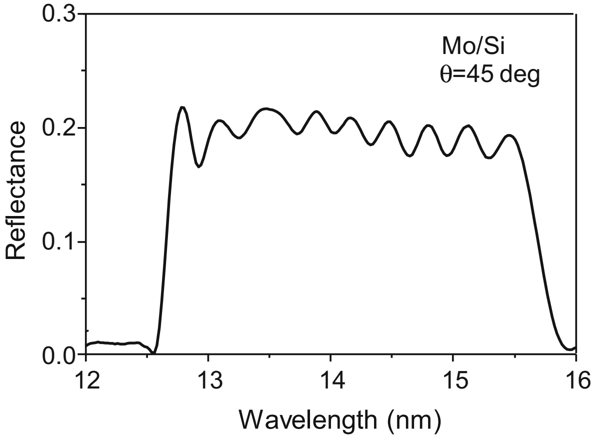

Fig. 3 Reflectance of broadband EUV optic

3 Diffractive Optics

Diffractive optics play a crucial role in EUV systems. Their relatively low cost, small size, and high resolution make them very attractive especially for use with low divergence sources. A drawback of these optics, however, is low efficiency. Below we describe a variety of methods to improve optical efficiency.

Diffractive optics [9–12] are normally patterned onto thin membrane substrates, however the limited transmission of these membranes in the EUV regime can significantly impact the total system efficiency. To avoid this problem, free-standing diffractive optics are required. This is especially important in the 40-nm wavelength

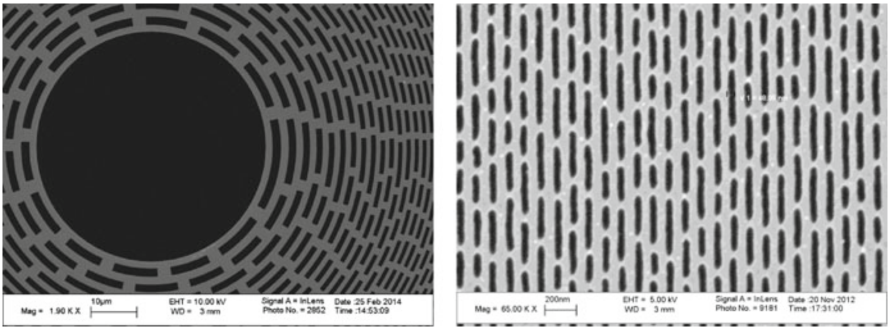

Fig. 4 Free-standing zoneplate for 47-nm operation. Bridges are placed between the zones to keep the whole free-standing structure together

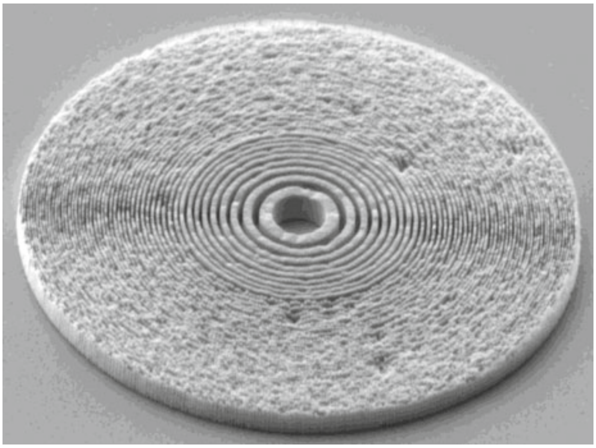

Fig. 5 Double patterned 760-nm thick zoneplate with 40-nm outer zone width

range where typical membrane transmission is extremely low. Figure 4 shows a free-standing zoneplate designed for use at 47 nm wavelength and having an outer zone width of 50 nm. Such zoneplates are used, for example, in soft-x-ray laser ablation mass spectroscopic imaging [13].

Another potentially important factor in zoneplate efficiency is zone thickness. This is especially true at shorter wavelengths. High resolution, high aspect ratio patterning, however, can be quite challenging. Multiple patterning provides a mechanism to mitigate the challenge. We have used double patterning of zoneplates [12] in the past to interlace lower density zones thereby surpassing the single exposure resolution limits of the patterning tool, but this same method can also be used to pattern multiple zoneplates directly on top of each other thereby increasing the total thickness again surpassing the single patterning limits. Figure 5 shows a 40-nm outer zone width zoneplate with a zone thickness of 760 nm (an aspect ratio of 19 to 1).

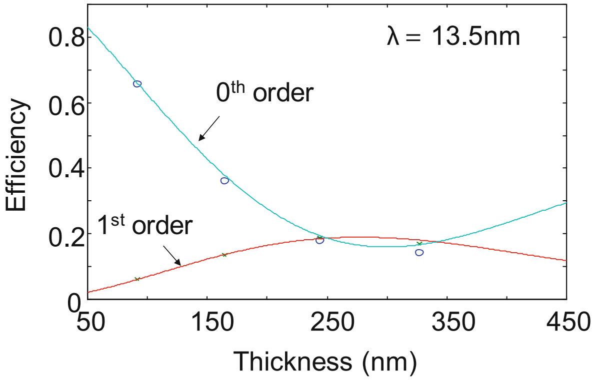

Fig. 6 Measured diffraction efficiency of etched silicon nitride test gratings as a function of groove thickness

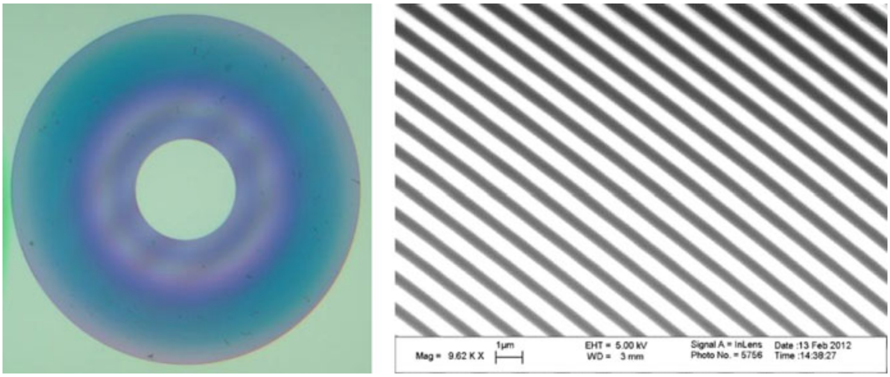

Fig. 7 Etched silicon nitride zoneplate used as HHG condenser optic

Another way to improve zoneplate efficiency is by way of phase shift materials. At 13.5 nm, silicon nitride, a common membrane material, exhibits good phase shift properties. This means that instead of patterning the zoneplate onto the membrane, we can also etch zoneplates into the membrane. Figure 6 shows diffraction efficiency measurements from silicon nitride test gratings where we have achieved an output diffraction efficiency of approximately 20 %. The experimental results are very well modelled based on the tabulated [14] optical properties of silicon nitride. The scatterometry measurements were performed using the Center for X-ray Optics Calibrations and Standards beamline. The nitride process has been successfully applied to operational zoneplates as shown in Fig. 7 which is used as an HHG condenser.

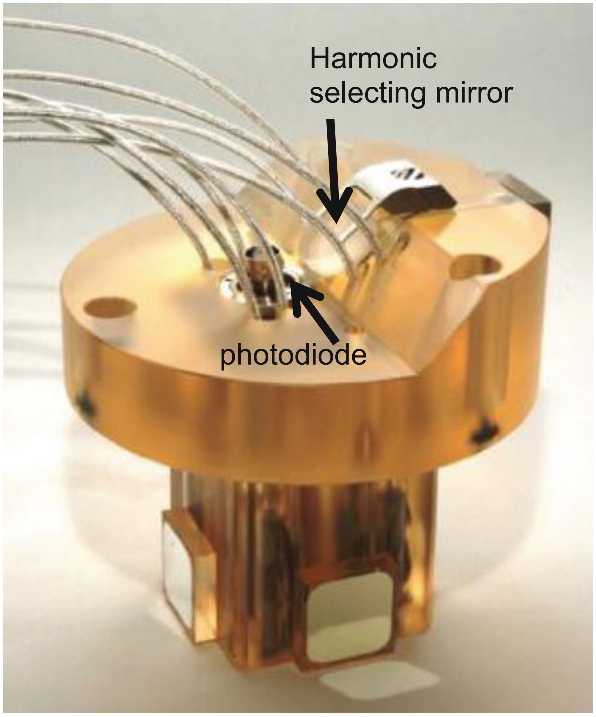

Fig. 8 Photograph of the scanning reflection EUV mask microscope optical housing. The zoneplate is mounted to the bottom of the housing and not visible in the photograph

4 Example System

Microscopy is a crucial scientific technique in the EUV regime. The optical components we have described above can be integrated with lab scale sources to make these capabilities available beyond the synchrotron community. An example of such a system is a scanning reflection EUV mask microscope [15] based on a commercial HHG source [16]. The system uses a harmonic selecting multilayer turning mirror to direct the light from the HHG source down at an angle of 6° from normal and towards a zoneplate placed 500-μm above the surface of a reflection EUV mask. The light is then focused to the mask and reflected back towards a photodiode integrated into the same optical housing holding the turning mirror and the zoneplate. The mask is then scanned under the focused beam to generate the two dimensional image. Figure 8 shows a photograph of the optical housing. The zoneplate is mounted to the bottom of the housing and not visible in the photograph. Figure 9 shows an image of 100-nm lines and spaces recorded from an EUV mask using the microscope described above [15].

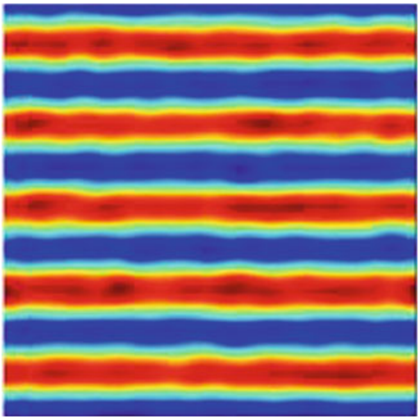

Fig. 9 Image of 100-nm lines and spaces recorded from an EUV mask using the optical system in Fig. 8

5 Summary

Good progress has been made recently in the area of compact coherent EUV sources. Using state of the art diffractive optics and reflection coatings, such sources can readily be integrated into a wide variety of optical systems including the scanning reflection EUV microscope described here.

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References

1. Reagan, B.A., Wernsing, K.A., Curtis, A.H., Furch, F.J., Luther, B.M., Patel, D., Menoni, C.S., Rocca, J.J.: Demonstration of a 100-Hz repetition rate gain-saturated diode-pumped table-top soft x-ray laser. Opt. Lett. **37**, 3624 (2012)
2. Zhang, X., Libertun, A.R., Paul, A., Gagnon, E., Backus, S., Christov, I.P., Murnane, M.M., Kapteyn, H.C., Bartels, R.A.: Highly coherent light at 13 nm generated by use of quasi-phase-matched high-harmonic generation. Opt. Lett. **29**, 1357 (2004)
3. Kim, S., Jin, J., Kim, Y., Park, I., Kim, Y., Kim, S.: High-harmonic generation by resonant plasmon field enhancement. Nature. **453**, 757–60 (2008)
4. Midorikawa, K.: High-order harmonic generation and attosecond science. Jpn. J. Appl. Phys. **50**, 9001 (2011)
5. Spiller, E.: Reflective multilayer coatings for the far UV region. Appl. Opt. **15**, 2333 (1976)
6. Underwood, J.H., Barbee, T.W. Jr.: Layered synthetic microstructures as Bragg diffractors for X rays and extreme ultraviolet: theory and predicted performance. Appl. Opt. **20**, 3027 (1981)
7. Takahashi, E., Nabekawa, Y., Midorikawa, K.: Generation of 10-mJ coherent extreme-ultraviolet light by use of high-order harmonics. Opt. Lett. **27**, 1920 (2002)
8. Aquila, A., Salmassi, F., Dollar, F., Liu, Y., Gullikson, E.: Developments in realistic design for aperiodic Mo/Si multilayer mirrors. Opt. Exp. **14**, 10073 (2006)
9. Schmahl, G., Rudolph, D. (eds.): X-Ray Microscopy, Proceedings International Symposium, Goettingen, Germany, Sept. 14–16, 1983, Vol. 43. Springer, Berlin (1984)
10. Anderson, E.H., Kern, D.: Nanofabrication of zone plates for X-Ray microscopy. In: Michette, A., Morrison, G., Buckley, C. (eds.) X-Ray Microscopy III. Springer, Berlin (1992)

11. Anderson, E.H.: Specialized electron beam nano-lithography for EUV and X-Ray diffractive optics. IEEE J. Quantum Electron. **42**, 27–35 (2006)
12. Chao, W., Tyliszczak, T., Kim, J., Fischer, P., Rekawa, S., Anderson, E.H.: Latest development of ultra-high resolution soft x-ray zone plate microscopy. X-Ray Microscopy X. (2010)
13. Kuznetsov, I., Filevich, J., Woolston, M., Bernstein, E., Crick, D., Carlton, D., Chao, W., Anderson, E., Rocca, J., Menoni, C.: Composition depth profiling by soft x-ray laser-ablation mass spectrometry. Proc. SPIE. **8849**, 88490G (2013)
14. http://henke.lbl.gov/optical_constants/
15. Kim, S., Lee, D., Park, J., Kim, E., Jeon, C., Cho, H., Jeon, B., choi, C., Anderson, C., Myakawa, R., Naulleau, P.: EUV mask imaging system based on the scanning reflective microscopy. 2013 International Symposium on Extreme Ultraviolet Lithography, Toyama, Japan, October 6–10, 2013, (proceedings available from SEMATECH, Albany, NY)
16. Yoo, B.: EUVO: EUV Light Generation System. 2013 International Symposium on Extreme Ultraviolet Lithography, Toyama, Japan, October 6–10, 2013, proceedings available from SEMATECH, Albany, NY