Sub-38 nm resolution tabletop microscopy with 13 nm wavelength laser light

G. Vaschenko, C. Brewer, F. Brizuela, Y. Wang, M. A. Larotonda, B. M. Luther, M. C. Marconi, J. J. Rocca, and C. S. Menoni

National Science Foundation Engineering Research Center for Extreme Ultraviolet Science and Technology and Department of Electrical and Computer Engineering, Colorado State University, Fort Collins, Colorado 80523

E. H. Anderson, W. Chao, B. D. Harteneck, J. A. Liddle, Y. Liu, and D. T. Attwood

National Science Foundation Engineering Research Center for Extreme Ultraviolet Science and Technology and Center for X-ray Optics, Lawrence Berkeley National Laboratory, and University of California, Berkeley, California 94720

Received December 19, 2005; accepted January 29, 2006; posted February 14, 2006 (Doc. ID 66741)

We have acquired images with a spatial resolution better than 38 nm by using a tabletop microscope that combines 13 nm wavelength light from a high-brightness tabletop laser and Fresnel zone plate optics. These results open a gateway to the development of compact and widely available extreme-ultraviolet imaging tools capable of inspecting samples in a variety of environments with a 15–20 nm spatial resolution and a picosecond time resolution. © 2006 Optical Society of America

OCIS codes: 180.7460, 110.7440, 140.7240.

Applications in nanoscience and nanotechnology demand nanometer-scale spatial resolution imaging tools. At present, the best spatial resolution for photon-based microscopes, 15 nm, has been obtained by using soft-x-ray illumination from a synchrotron source.[1] However, the widespread use of short-wavelength microscopy requires the development of more compact and more widely accessible instruments. Here we establish a path to the realization of very high-resolution (e.g., 15 nm) tabletop analytical imaging tools. By combining the 13 nm wavelength output from a tabletop laser with zone plate optics, images with sub-38 nm resolution were obtained with exposures as short as several seconds. This type of compact microscope that takes advantage of the high brightness, high monochromaticity, and directionality of new tabletop soft-x-ray lasers will allow imaging of objects in a variety of environments.

In addition to the experiments conducted at synchrotron facilities, a variety of imaging experiments have been carried out by using both coherent and incoherent short-wavelength sources.[2–10] Early imaging work with short-wavelength lasers demonstrated submicrometer resolution with a recombination laser at $\lambda = 18.2$ nm.[3] A resolution of 75 nm was reported for the very large fusion-driver laser NOVA used to pump a soft-x-ray laser ($\lambda = 4.48$ nm), which was limited to firing several shots a day.[4] In the past several years smaller-scale short-wavelength sources including high-order harmonics,[5,6] extreme-ultraviolet (EUV) lasers,[7,8] and incoherent laser-plasma-based sources[9,10] have been used for submicrometer resolution imaging. Of these experiments, the best performance in terms of spatial resolution, reported as sub-100 nm, has been obtained with an incoherent laser-created plasma source emitting at $\lambda = 3.37$ nm in a 2π steradian angle.[10]

Our tabletop imaging system, schematically shown in Fig. 1, is based on a highly directed laser source that allows for efficient collection of light. The illumination source is a 5 Hz repetition rate tabletop laser, capable of generating highly monochromatic light ($\Delta\lambda/\lambda < 1 \times 10^{-4}$) with microwatt average power at wavelengths near 13 nm.[11,12] A condenser zone plate collects the laser light and focuses it onto the test pattern, and an objective zone plate forms the image of the test pattern onto a backilluminated charge coupled detector (CCD). The EUV laser light is generated by amplification of spontaneous emission in a transient population inversion created by collisional electron impact excitation in a line focus laser-created plasma. The plasma is produced by heating a 4 mm long slab target at grazing incidence[13,14] with a high-intensity optical laser pulse from a chirped pulse amplified Ti:sapphire laser system. To conduct the imaging experiments described in this Letter, laser average powers of 1–2 μW at $\lambda = 13.9$ and $\lambda = 13.2$ nm were produced in transitions of nickellike silver and cadmium ions, respectively, by heating precreated plasmas of these materials with laser pulses of 1 J energy and about 8 ps duration impinging at an optimized grazing incidence angle of

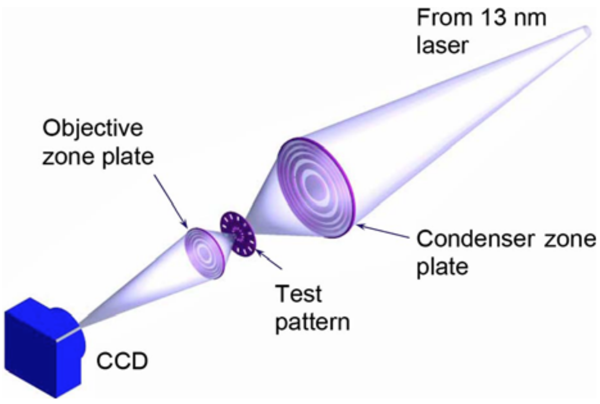

Fig. 1. (Color online) Schematic diagram of the 13 nm wavelength imaging system.

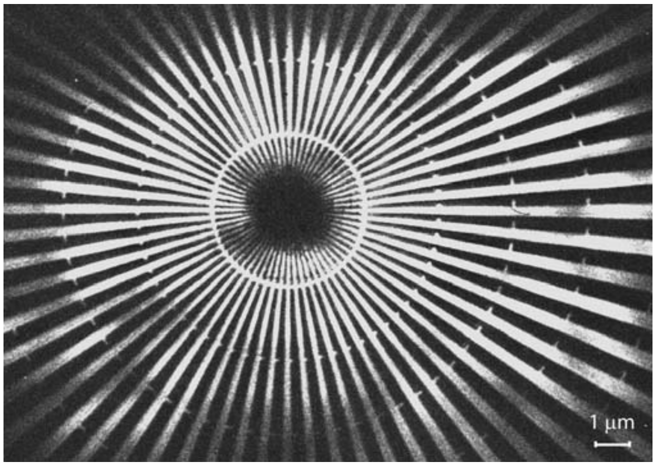

Fig. 2. Large-field-of-view image of a set of radial spokes obtained with a $\Delta r = 80\,\mathrm{nm}$ zone plate at 13.9 nm laser wavelength illumination in a 20 s exposure. The lines resolved in the center of the pattern are at a 60 nm half-period.

23°.[11,12] The EUV laser output is highly directional, characterized by a divergence of ~7 mrad in the plane of incidence of the pump beam.

The condenser and objective zone plates were fabricated by electron beam lithography[15] in a 120 nm thick nickel film supported by a 100 nm Si_3N_4 membrane that is ~40% transparent to the incident 13 nm light. The condenser zone plate has a diameter of 5 mm and consists of 12,500 zones of decreasing width down to 100 nm. It has a numerical aperture NA=0.07 and a focal distance of 38 mm for the wavelength of 13.2 nm. Two different objective zone plates were used. One has a diameter of 0.2 mm and contains 625 zones with an outermost zone width (Δr) of 80 nm. The second one has a 0.1 mm diameter with $\Delta r = 50$ nm. Chromatic aberrations are negligible as a result of the inherently high monochromaticity of the EUV laser light. Images were recorded with a thermoelectrically cooled CCD camera with a backilluminated 2048×2048 array of $13.5\,\mu\mathrm{m} \times 13.5\,\mu\mathrm{m}$ pixels. Microscope magnifications of 290–1750× were obtained by selecting objective working distances very close to its focal length and objective zone plate to CCD camera distances in the 0.335–0.635 m range.

The microscope's performance was evaluated by imaging a test pattern consisting of a thin metalized membrane with openings of various shapes and dimensions that was also fabricated by electron beam lithography by the same process described for the zone plates.[15] This pattern includes a set of lines and spaces with nominal 1:1 line/space ratios with half-periods ranging from 38 to 310 nm. The sample also contains a set of 64 radial spokes decreasing in width down to ~40 nm as they converge toward the center of the circular pattern. Figure 2 shows an image of the radial spoke pattern obtained with the objective zone plate of $\Delta r = 80$ nm, using $\lambda = 13.9$ nm illumination and an exposure time of 20 s (100 laser pulses at a 5 Hz repetition rate). The central part of the image shows lines with a 60 nm half-period that are clearly visible. The acquisition of images like this, which have a relatively large field of view of $\sim 12\,\mu\mathrm{m} \times 20\,\mu\mathrm{m}$, is facilitated by the high brightness of the laser and its directionality, which allows the condenser to efficiently collect the laser emission and focus it onto the test pattern.

The characteristics of both the optics and the illumination play a role in determining the spatial resolution of the zone plate microscope, defined here as the half-period of the smallest set of dense lines for which the modulation depth in the image's intensity profile (lineout) is 26.5% or better (Rayleigh-like modulation[16]). The resolution can be expressed as $k_1\lambda/\mathrm{NA}$, where k_1 is an illumination-dependent and resolution test-specific constant, λ is the wavelength, and NA is the numerical aperture of the objective.[16] For a zone plate used at high magnification $\mathrm{NA} = \lambda/(2\Delta r)$,[17] and the spatial resolution definition simplifies to $2k_1\Delta r$. In our EUV microscope the illumination at the object plane is partially coherent as a result of the combined effect of the condenser and the partial coherence of the source. Considering the slightly off-axis illumination taking place in our experiment, we estimate $k_1 \approx 0.32$,[17] which suggests a spatial resolution limit for the instrument of about 32 nm.

The actual spatial resolution of the microscope was experimentally determined by imaging the portion of the test pattern containing the periodic lines and spaces. Figure 3 shows images of gratings with the smallest available half-periods of 50 and 38 nm with a nominal 1:1 line/space ratio. The images were obtained with the $\Delta r = 50$ nm objective at $\lambda = 13.2$ nm by using a 20 s exposure. The ~70% intensity modulation in the image of the smallest lines clearly demon-

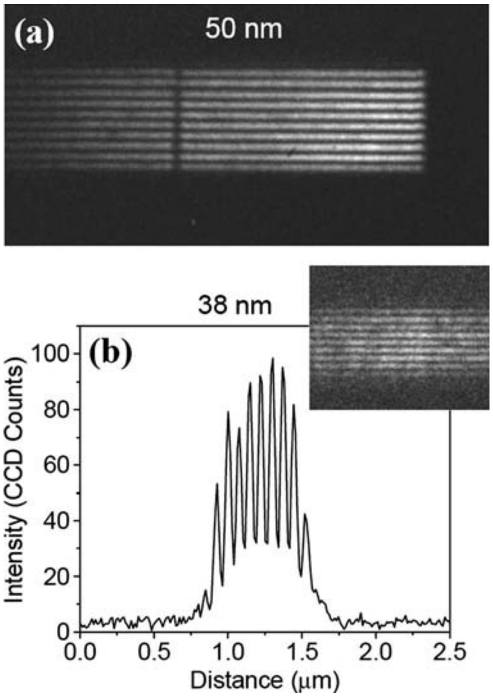

Fig. 3. Images of the (a) 50 and (b) 38 nm half-period line patterns obtained with a $\Delta r = 50$ nm zone plate and 13.2 nm wavelength laser illumination by using a 20 s exposure time. The cross section of the 38 nm lines image demonstrates that the microscope resolution is better than 38 nm.

strates that the spatial resolution of the microscope is better than 38 nm, to our knowledge the highest resolution demonstrated to date with a tabletop short-wavelength imaging system. This result is made possible by the combination of the high-brightness illumination provided by the EUV laser and nearly aberration-free diffractive optics. The resolution of the microscope reported here could be further improved by using an objective zone plate with smaller outermost zone width and increased numerical aperture. For example, the use of a zone plate with an outer zone width of 20 nm could potentially yield images with a resolution of $\sim 15-18$ nm with 13 nm wavelength laser illumination. Additional improvements in resolution can be expected to result from future extensions of high-repetition-rate tabletop lasers to shorter wavelengths. Furthermore, the high brightness and short pulse duration of the compact EUV laser will permit time-resolved imaging of ultrafast phenomena in many applications.

This work was supported by the Engineering Research Centers Program of the National Science Foundation under NSF award EEC-0310717. The work at Lawrence Berkeley National Laboratory also received partial support from the U.S. Department of Energy, Office of Basic Energy Sciences, and the Defense Advanced Research Projects Agency. We also acknowledge the support of the W. M. Keck Foundation. G. Vaschenko's e-mail address is vaschen@engr.colostate.edu.

References

1. W. Chao, B. D. Harteneck, J. A. Liddle, E. H. Anderson, and D. T. Attwood, Nature **435**, 1210 (2005).
2. J. A. Trail and R. L. Byer, Opt. Lett. **14**, 539 (1989).
3. D. S. DiCicco, D. Kim, R. Rosser, and S. Suckewer, Opt. Lett. **17**, 157 (1992).
4. L. B. Da Silva, J. E. Trebes, S. Mrowka, T. W. Barbee, Jr., J. Brase, J. A. Koch, R. A. London, B. J. MacGowan, D. L. Matthews, D. Minyard, G. Stone, T. Yorkey, E. Anderson, D. T. Attwood, and D. Kern, Opt. Lett. **17**, 754 (1992).
5. M. Wieland, C. Spielmann, U. Kleineberg, T. Westerwalbesloh, U. Heinzmann, and T. Wilhein, Ultramicroscopy **102**, 93 (2005).
6. A. R. Libertun, X. Zhang, A. Paul, D. Raymondson, E. Gershgoren, E. Gagnon, S. Backus, M. M. Murnane, H. C. Kapteyn, R. A. Bartels, Y. Liu, and D. T. Attwood, in *Conference on Lasers and Electro-Optics*, Vol. 96 of OSA Trends in Optics and Photonics (Optical Society of America, 2004), paper JMD4.
7. M. Kishimoto, M. Tanaka, R. Tai, K. Sukegawa, M. Kado, N. Hasegawa, H. Tang, T. Kawachi, P. Lu, K. Nagashima, H. Daido, Y. Kato, K. Nagai, and H. Takenaka, J. Phys. IV **104**, 141 (2003).
8. G. Vaschenko, F. Brizuela, C. Brewer, M. Grisham, H. Mancini, C. S. Menoni, M. Marconi, and J. J. Rocca, Opt. Lett. **30**, 2095 (2005).
9. I. A. Artioukov, A. V. Vinogradov, V. E. Asadchikov, Y. S. Kasyanov, R. V. Serov, A. I. Fedorenko, V. V. Kondratenko, and S. A. Yulin, Opt. Lett. **20**, 2451 (1995).
10. M. Berglund, L. Rymell, M. Peuker, T. Wilhein, and H. M. Hertz, J. Microsc. (Oxford) **197**, 268 (2000).
11. J. J. Rocca, Y. Wang, M. A. Larotonda, B. M. Luther, M. Berrill, and D. Alessi, Opt. Lett. **30**, 2581 (2005).
12. Y. Wang, M. A. Larotonda, B. M. Luther, D. Alessi, M. Berrill, V. N. Shlyaptsev, and J. J. Rocca, Phys. Rev. A **72**, 053807 (2005).
13. R. Keenan, J. Dunn, P. K. Patel, D. F. Price, R. F. Smith, and V. N. Shlyaptsev, Phys. Rev. Lett. **94**, 103901 (2005).
14. B. M. Luther, Y. Wang, M. A. Larotonda, D. Alessi, M. Berrill, M. C. Marconi, J. J. Rocca, and V. N. Shlyaptsev, Opt. Lett. **30**, 165 (2005).
15. E. H. Anderson, D. L. Olynick, B. Harteneck, E. Veklerov, G. Denbeaux, W. Chao, A. Lucero, L. Johnson, and D. Attwood, J. Vac. Sci. Technol. B **18**, 2970 (2000).
16. M. Born and E. Wolf, *Principles of Optics* (Cambridge U. Press, 1999), pp. 461–472; *Principles of Optics* (Cambridge U. Press, 1999), pp. 595–606.
17. J. M. Heck, D. T. Attwood, W. Meyer-Ilse, and E. H. Anderson, J. X-Ray Sci. Technol. **8**, 95 (1998).