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Single shot extreme ultraviolet laser imaging of nanostructures with wavelength resolution

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We have demonstrated near-wavelength resolution microscopy in the extreme ultraviolet. Images of 50 nm diameter nanotubes were obtained with a single ~1 ns duration pulse from a desk-top size 46.9 nm laser. We measured the modulation transfer function of the microscope for three different numerical aperture zone plate objectives, demonstrating that 54 nm half-period structures can be resolved. The combination of near-wavelength spatial resolution and high temporal resolution opens myriad opportunities in imaging, such as the ability to directly investigate dynamics of nanoscale structures.

OCIS codes: 180.7460, 110.7440, 140.7240.

Conventional visible light microscopy, the most convenient method to image small objects, is limited in resolution to about 200 nm [1]. A direct approach to overcome this limitation is the use of shorter wavelength extreme ultraviolet (EUV) or soft x-ray (SXR) light [2-11]. The highest spatial resolution achieved to date was obtained at the Advanced Light Source, a third generation synchrotron, where images with 15 nm half-period spatial resolution were acquired in exposure times of several seconds using 1.52 nm wavelength SXR light [2]. The need for compact and more broadly accessible full-field optical microscopes has motivated the development of microscopes based on high-harmonic light sources [5, 6], plasma sources [7], and EUV/SXR lasers [8-11]. However, in all cases the spatial resolution achieved was several times the wavelength and/or required long exposures.

In this letter we report what is to our knowledge the first EUV microscope that can obtain images with a spatial resolution approaching the wavelength of illumination, in this case $\lambda = 46.9$ nm ($h\nu = 26.4$ eV). Moreover, this microscope can obtain high spatial resolution images with a single laser shot, corresponding to ~1 ns temporal resolution, opening the possibility to investigate dynamics of nanoscale structures. This is possible due to the high brightness of the laser source, the high throughput of the optics, and the ability to tailor the spatial coherence of the laser to reduce coherence effects that can degrade single shot images. The entire microscope is extremely compact, occupying an area of 0.4 m × 2.5 m. The combination of these attributes results in the demonstration of a high-resolution tool that can rapidly acquire full-field images for practical laboratory use in a broad range of applications.

The microscope is schematically illustrated in Figure 1. Two spherical Sc/Si multilayer mirrors arranged in a Schwarzschild configuration with 13% throughput condense the light from the output of the laser onto the sample. A freestanding objective zone plate lens projects the image onto a charge-coupled device (CCD) detector with 13.5 μm pixels. The laser beam is created via a highly ionized plasma column that is generated by fast electrical discharge excitation of an argon-filled capillary [12]. It emits laser pulses with ~10 μJ of energy (2.4×10^{12} photons/pulse) and high monochromaticity ($\Delta\lambda/\lambda \approx 5x10^{-5}$), which is ideal for the use of chromatically dependent zone plates. The plasma in the capillary has a convex axisymmetric electron density profile with an on-axis maximum that causes refraction of the amplified light. This provides a mode selection mechanism that filters higher order modes and reduces the effective transverse source size significantly as the gain medium lengthens. The capillary length of 22 cm selected for these experiments produces optimized, partially coherent pulses for illumination that limit speckle effects that can degrade image quality, while still providing sufficient photon flux for single shot imaging.

In this work we used three objective zone plates with outer zone widths of Δr = 200 nm, 124 nm, and 73 nm (NA = 0.12, 0.19 and 0.32, respectively). The zone plates were produced by e-beam lithography on ~100 nm Si_3N_4 membranes [13]. They are freestanding, containing pseudo-random supportive spokes between the zones, to allow a throughput near the full 10% efficiency of the first diffraction order.

The resolving ability of the microscope was evaluated by measuring the modulation transfer function (MTF) for each zone plate objective. Here we define the spatial resolution to be the half-period of a grating for which its image exhibits an intensity modulation of 0.265, derived from the Rayleigh criterion for two imaged point sources [14, 15]. To determine the MTF for each objective, we obtained single shot images of freestanding transmission gratings with spatial half-periods ranging from 300 nm to 54 nm.

Figures 2(a) and 2(c) are EUV images of two of the smallest half-period gratings, 70 nm and 54 nm, obtained using the Δr = 73 nm zone plate. The magnification was 1200×, corresponding to a pixel size of 11 nm at the sample. Scanning electron microscope (SEM) images of portions of the gratings are shown in the bottom left corners of the EUV images. Figures 2(b) and 2(d) show intensity lineouts for the two images, with average modulation values of 0.83 and 0.33, respectively. Both images satisfy the Rayleigh-like criterion, and thus are considered fully resolved. The MTF for each zone plate is shown in Figure 3. For each image, multiple intensity lineouts were sampled and averaged to obtain the corresponding value and error bar. As expected, for a constant wavelength of illumination, the MTF curve extends to higher spatial frequencies as the numerical aperture of the objective increases. For the Δr = 200 nm, 124 nm, and 73 nm zone plates, near diffraction-limited half-period spatial resolution values of 120 nm, 80 nm, and 54 nm, respectively, were measured. With a spatial resolution of 54 nm, this microscope is to our knowledge the first in the EUV region with the ability to resolve features of dimensions closely approaching the wavelength of illumination.

To illustrate the use of the microscope, we selected an object of dimensions similar to the measured resolution limit of the microscope. We imaged carbon nanotubes with diameters of ~50 nm, as determined by SEM images, which were deposited onto a ~100 nm thick Si membrane with ~30% transmission at a wavelength of 46.9 nm. Figure 4 is a single shot image of an entanglement of several carbon nanotubes, in which features such as nanotube bifurcations are visible.

Although the images presented herein were obtained collecting the transmitted light through the samples, the microscope can be readily reconfigured to acquire images in reflection mode [10]. Furthermore, the ability of this EUV microscope to resolve wavelength-size features with a single laser shot will enable the study of dynamics on nanosecond time scales. Based on these results, we anticipate that recently developed high brightness tabletop lasers at wavelengths near 13 nm [16] will enable the acquisition of images with spatial resolution approaching 15 nm and picosecond temporal resolution. At these shorter wavelengths, microscopes will be particularly advantageous as mask inspection tools for the EUV lithography industry. Moreover, these practical compact EUV and SXR laser-based full-field microscopes will allow the study of ultrafast processes with nanometer-scale resolution, becoming an enabling tool for a wide range of nanoscience and nanotechnology applications.

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Figures

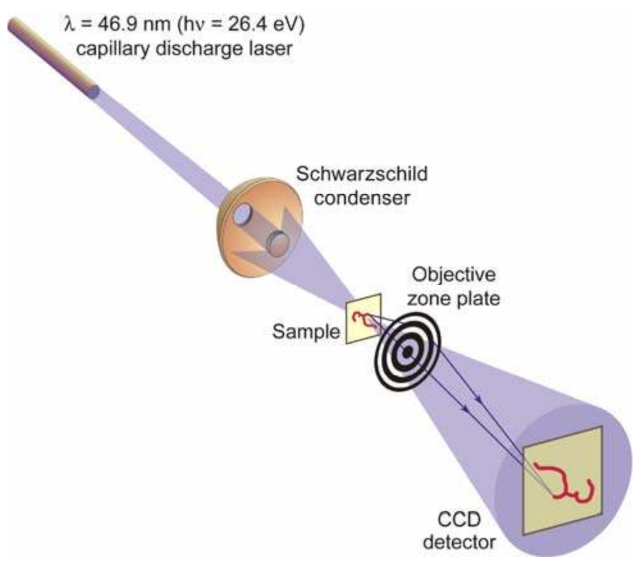

Fig. 1. (Color online) Schematic setup of the compact 46.9 nm wavelength microscope.

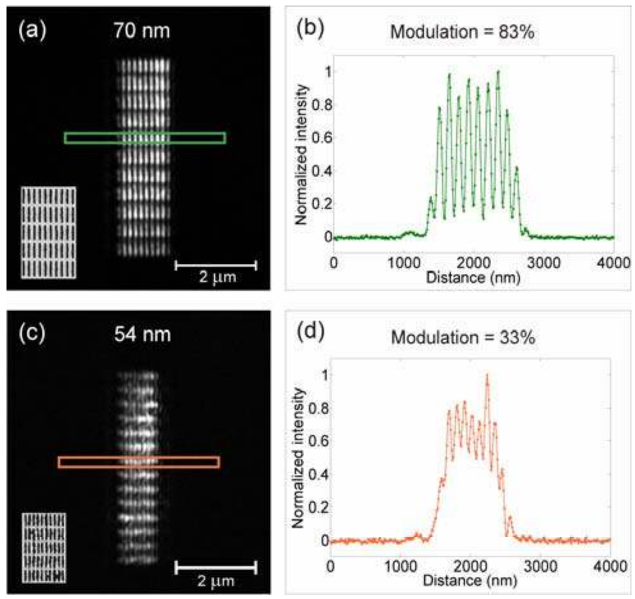

Fig. 2. (Color online) Single shot EUV images of (a) a 70 nm half period grating and (b) its corresponding lineout with an 83% intensity modulation, and (c) a 54 nm half-period grating with (d) an intensity lineout showing an average modulation of 33%. The EUV images were acquired using a zone plate objective having an outer zone width of Δr = 73 nm (NA = 0.32). SEM images of portions of the gratings are displayed in the lower corner of the EUV images.

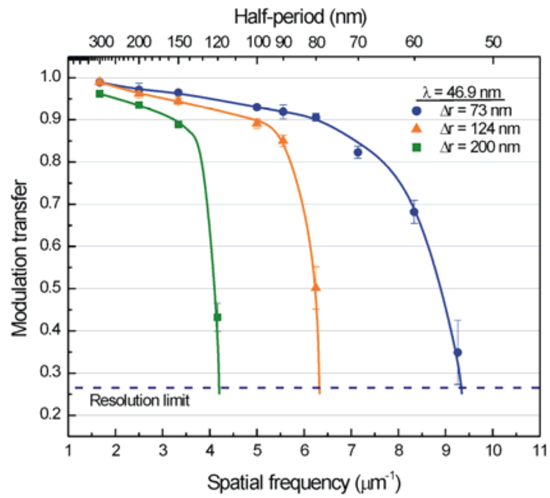

Fig. 3. (Color online) Measured MTFs for objective zone plates with outer zone widths of Δr = 200 nm, 124 nm, and 73 nm (NA = 0.12, 0.19 and 0.32). The intensity modulation transfer is graphed as a function of the half-period of the grating sample and the spatial frequency, the inverse of the spatial period. The modulation transfer values were obtained by averaging multiple intensity lineouts within an image, and the curves were added to guide the eye. For the Δr = 200 nm, 124 nm, and 73 nm zone plates, Rayleigh-like resolution values of 120, 80 nm, and 54 nm, respectively, were measured.

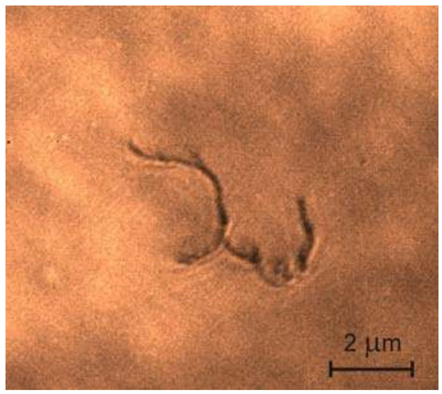

Fig. 4. (Color online) Single shot image of an entanglement of 50 nm diameter carbon nanotubes. This image was obtained using the Δr = 73 nm objective lens and a wavelength of 46.9 nm. Features such as nanotube bifurcations are visible.