Advances in full field microscopy with table-top soft x-ray lasers

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ABSTRACT

We describe recent advances in the demonstration of table-top full field microscopes that use soft x-ray lasers for illumination. We have achieved wavelength resolution and single shot exposure operation with a very compact 46.9 nm microscope based on a desk-top size capillary discharge laser. This λ=46.9 nm microscope has been used to captured full field images of a variety of nanostructure systems and surfaces. In a separate development we have demonstrated a zone plate microscope that uses λ=13.2 nm laser illumination to image absorption defects in a extreme ultraviolet lithography (EUVL) mask in the same geometry used in a 4× demagnification EUVL stepper. Characterization of the microscope's transfer function shows it can resolve 55 nm half period patterns. With these capabilities, the λ=13.2 nm microscope is well suited for evaluation of pattern and defect printability of EUVL masks for the 22 nm node.

Keywords: soft x-rays, microscopy, extreme ultraviolet lithography, defect inspection, nanoscale imaging

1. INTRODUCTION

The development of coherent and incoherent table-top sources of extreme ultraviolet (EUV) and soft x-ray (SXR) light has stimulated the implementation of full field microscopes which owing to the short wavelength illumination provide a spatial resolution significantly better than that of visible microscopes. [1-10]. In this paper we summarize recent advances in the SXR microscopy enabled by table-top soft x-ray lasers developed at Colorado State University [11, 12]. Equipped with diffractive and reflective optics, these full field microscopes have been used to image nanostructures, surfaces and absorption patterns in extreme ultraviolet masks with a spatial resolution better than 50 nm and exposures ranging from 20 sec down to a single laser shot.

## 2. SINGLE SHOT -WAVELENGTH RESOLUTION IMAGING WITH A COMPACT SXR MICROSCOPE

We have built a compact microscope that combines the output from a 46.9 nm wavelength desk-top Ne-like Ar laser [11]with high quality reflective and diffractive optics allowing transmission and reflection mode imaging with 50 nm spatial resolution. [6, 7]The microscope, including the laser source has a very small foot-print, occupying a portion of a 8×6 sq ft optical table. A picture of the system is shown in Fig. 1.
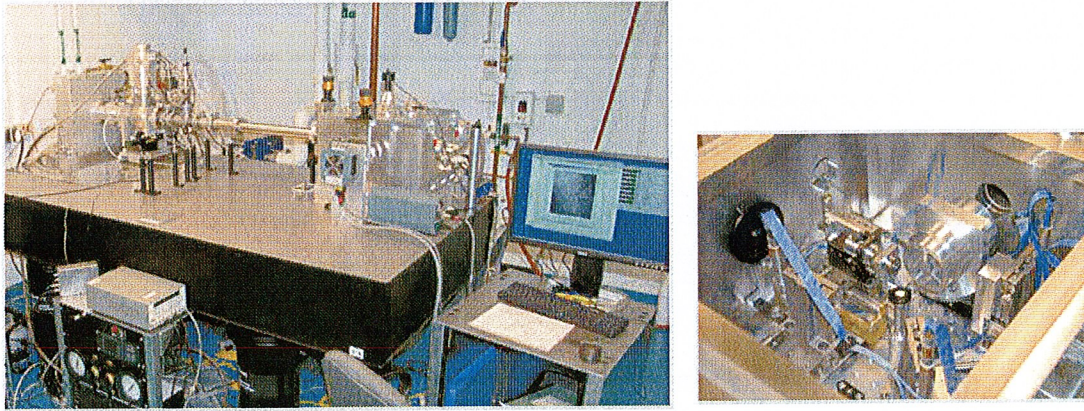
Fig. 1. Left) Picture of the SXR microscope. The laser unit on the left is connected through standard vacuum fittings to the microscope chamber on the right. The entire system fits on a small optical table. Right) Picture of the inside of the microscope chamber.

This microscope uses a Sc/Si coated Schwarzschild condenser to illuminate the object and free standing Fresnel zone plate objectives. Three objectives with 0.12, 0.20, and 0.32 NA are available for this microscope. [13]

The resolving power for each objective zone plate was evaluated constructing modulation transfer curves shown in Fig. 2. The data were collected from the modulation of intensity cross-sections of single shot images of transmission gratings with half-periods varying from 54 nm to 300 nm. For each objective zone plate, images of the different gratings were obtained and the intensity modulation calculated. Figure 2 shows that the resolution of the microscope increases with increased numerical aperture (NA) of the objective. The highest spatial resolution obtained with the 0.32 NA objective is ~ 50 nm. These are the first results reported on a SXR microscope that achieves wavelength resolution.
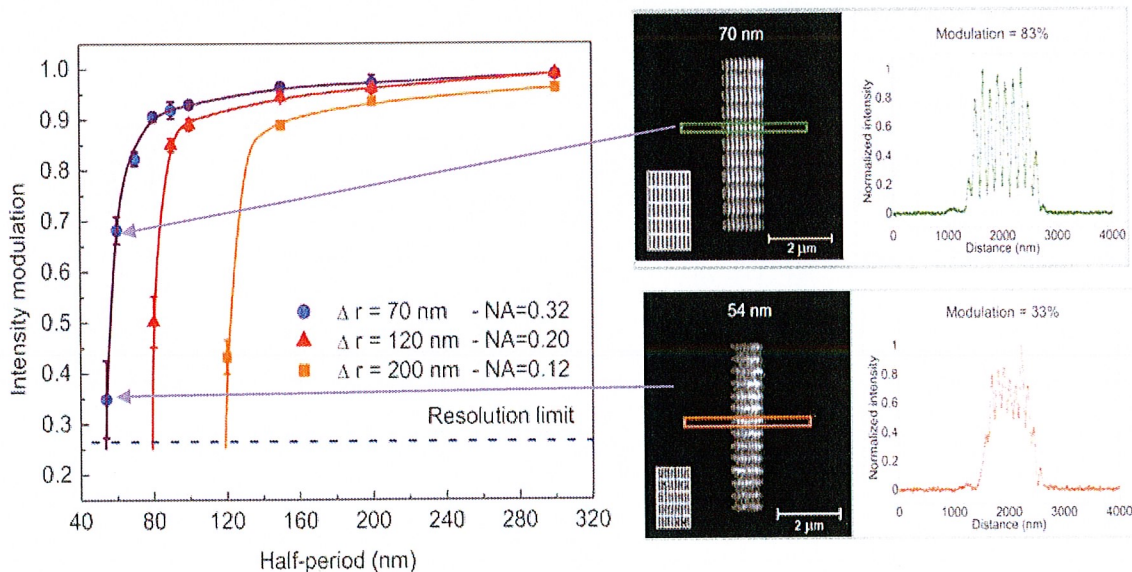
Fig. 2. Measured Modulation Transfer Functions (MTFs) for three objective zone plates. With a 0.32 NA zone plate, a spatial resolution of 50 nm can be achieved.

Several samples were prepared and imaged with the λ=46.9 nm microscope to illustrate its capabilities. For transmission imaging sample preparation consisted of laying the objects onto a ~ 100 nm thick Si window fabricated on a 5×5 mm^2 Si wafer. At λ=46.9 nm, the Si window transmitted ~30% of the light. A transmission SXR image of a single diatom

obtained using the 0.32 NA objective with an exposure of 5 seconds is shown in Fig. 3. The fine structure of the diatom is well resolved.
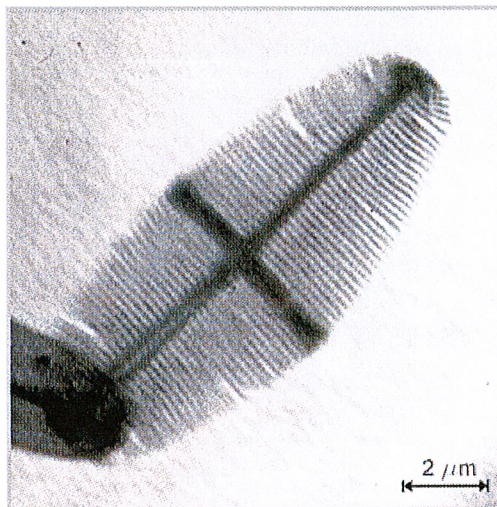

Fig. 3. SXR image of a single diatom obtained with a 5 second exposure using the 0.32 NA objective.

The microscope has also been used to image carbon nanotubes with a diameter of ~ 50 nm. Fig. 4.a) is a SXR image of a single nanotube obtained with *one* laser shot. Figure 4.b) shows the same tube as imaged by a scanning electron microscope (SEM) for comparison. [7]
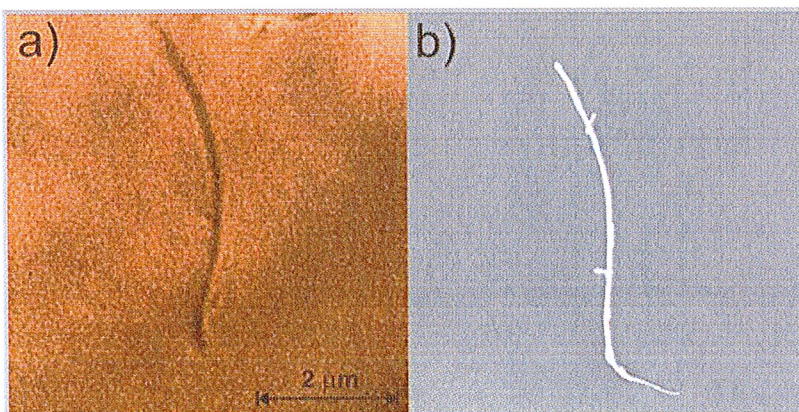

Fig. 4. a) Single shot SXR image of a ~50 nm wide carbon nanotube on a Si membrane. The image was obtained with a 0.32 NA zone plate. b) Same carbon nanotube as imaged by SEM.

The microscope also operates in reflection configuration. This is accomplished by positioning the sample at 45° with respect to the direction of the illumination. [6] Because the objective is also at 45° with respect to the sample, its depth of focus limits to ~ 2 μm the field of view where the image is in focus. Nevertheless, very good quality images with short exposures (< 20 sec) can be obtained. This is significant because the reflectivity of most materials is low (<5%) at λ=46.9 nm. Figure 5 shows an SXR image of a GaAs nanowire bridging two Al contacts grown on a Si wafer was imaged. The image was obtained with the 0.20 NA objective and an exposure time of 5 seconds corresponding to 15 laser shots.
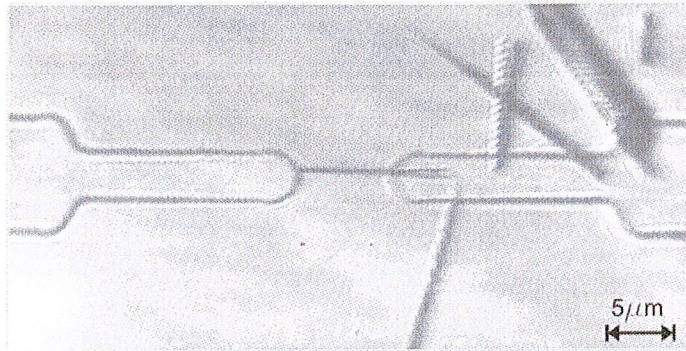
Fig. 5. Reflection image of a GaAs nanowire between two Al contacts on a Si wafer. The SXR image was acquired with a 0.20 NA objective zone plate. In the image, other nanowires that did not successfully bridge the contacts can be seen.

The small penetration depth of the $\lambda = 46.9$ nm light combined with the high resolution of the microscope are ideal for the study of surface phenomena in materials. Fig. 6 shows the SXR imaged of the Zr surface obtained with the 0.20 NA objective. In the image grain boundaries and defects are clearly observed.
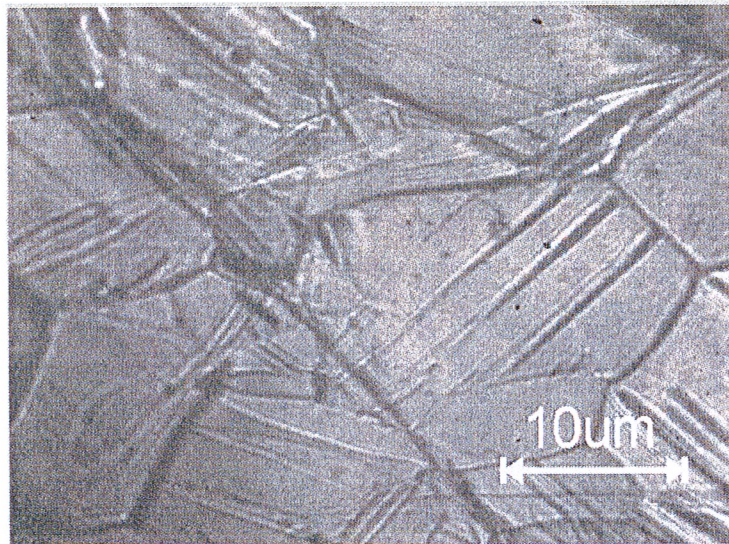

Fig. 6. Reflection mode image of the surface of a strained Zr sample. The image was obtained with a 0.20 NA objective and an exposure time of 5 seconds.

3. 13.2 NM WAVELENGTH ACTINIC INSPECTION MICROSCOPE

We demonstrated in 2006 transmission imaging at $\lambda = 13.2$ nm with a spatial resolution better than 38 nm, using a zone plate microscope illuminated by a table-top Ni-like Cd laser. [4] With the specific goal of imaging and characterizing defects on Mo/Si reflective EUVL masks, we have recently demonstrated the challenging reflection configuration using a table-top zone plate microscope operating at at $\lambda = 13.2$ nm. [8]

The $\lambda = 13.2$ nm reflection microscope is designed to mimic the imaging conditions of a 4× demagnification, 0.25 NA, EUVL stepper. This was accomplished by setting the angle of the illumination at 6 degrees with respect to the normal

to the mask surface, by choosing the numerical aperture of the objective to be one forth the NA of the EUVL stepper and by matching the numerical apertures of the condenser to that of the objective. In this way, any printable defect on a EUVL mask is imaged under the same illumination conditions as it would print. This design follows that of an actinic microscope demonstrated by some of us that uses the Advanced Light Source for illumination. [14] Figure 7 shows a schematic diagram of the setup along with a picture of the microscope chamber where the beam path has been marked. The $\lambda=13.2$ nm laser output is guided by a Mo/Si mirror to the condenser that illuminates the test object. The condenser with 0.065NA was fabricated by electron beam lithography on a Si3N4 membrane. The structure also contains an aperture that clears the path for the zone plate objective to form the image on the CCD detector at normal incidence to the mask surface. An off-axis design was used for the objective zone plate. In this design illustrated in Fig. 8, an off-axis pupil is overlapped onto a 'parent' zone plate, limiting the numerical aperture of the lens. Because the zones within the pupil are concentric to the axis of the 'parent' zone plate, the image is projected onto a plane perpendicular to the lens. Due to the small angle of incidence of the incoming light, a region opposite to the lens is left uncoated, creating a thin Si_3N_4 window that allows ample throughput of the 13.2 nm light. The insert in Fig. 8 shows the outer zone widths of the zone plate that are 40 nm wide. The effective NA of the objective equals 0.065NA matching that of the condenser.
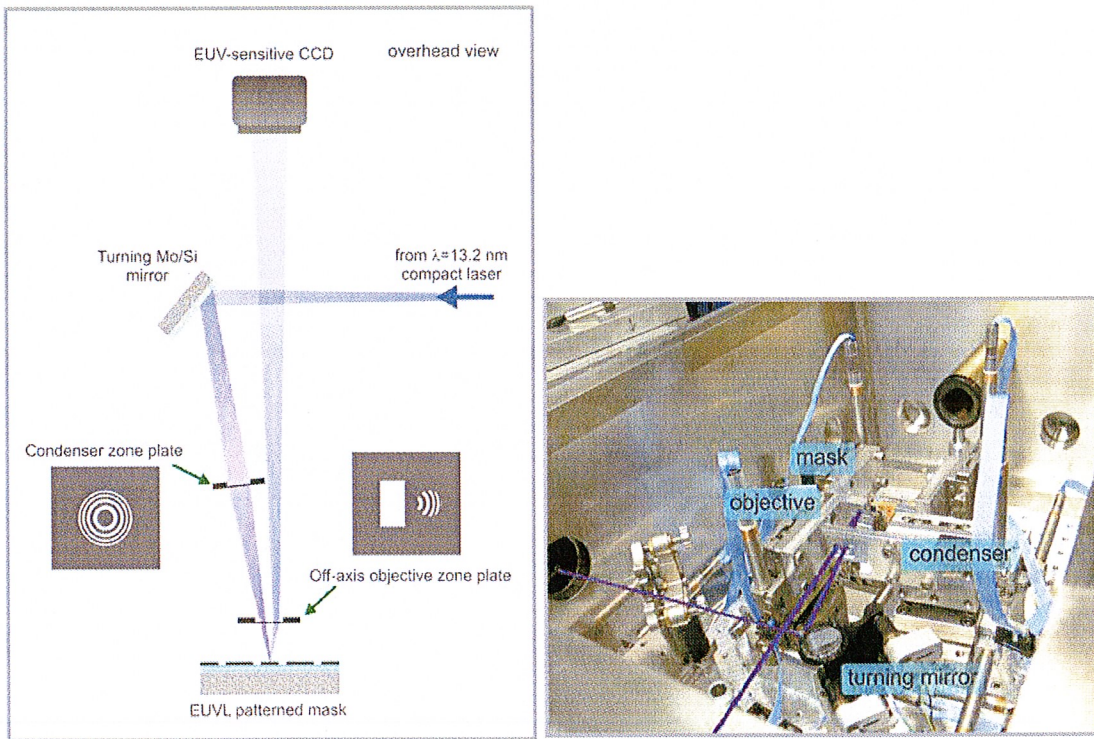

Fig. 7. a) Schematic representation of the 13.2 nm wavelength microscope for EUVL mask inspection. b) Photograph of the microscope chamber. The beam enters the chamber from the port on the left of the image. The line was added to indicate the beam path.

A EUVL mask simile consisting of a Mo/Si stack with ~ 63% reflectance at $\lambda=13.2$ nm containing absorption features consisting of elbow patterns with half-pitch lines ranging from 80 to 200 nm was fabricated and used to test the microscope. Figure 9 shows SXR reflection images of (a) 80 nm, (b) 100 nm, (c) 120 nm, and (d) 140 nm half-pitch structures with their corresponding intensity cross-sections. The images have a field-of-view of 25 μm^2 and were obtained with a 20 second exposure time. The high modulation values indicate that even the 80 nm features are fully resolved. The fact that the vertical and horizontal lines can be resolved at the same time indicates that the astigmatism of the system is low.
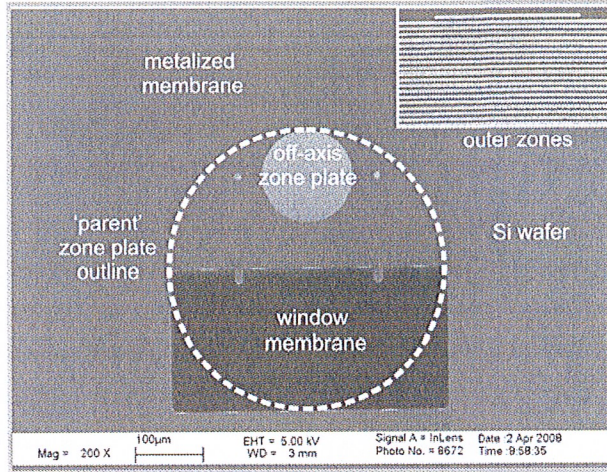
Fig. 8. SEM image of the off-axis objective zone plate. The insert in the top-right corner of the image shows a magnified image of the 40 nm outer zones of the zone plate. The effective NA of the off-axis objective is 0.0625.
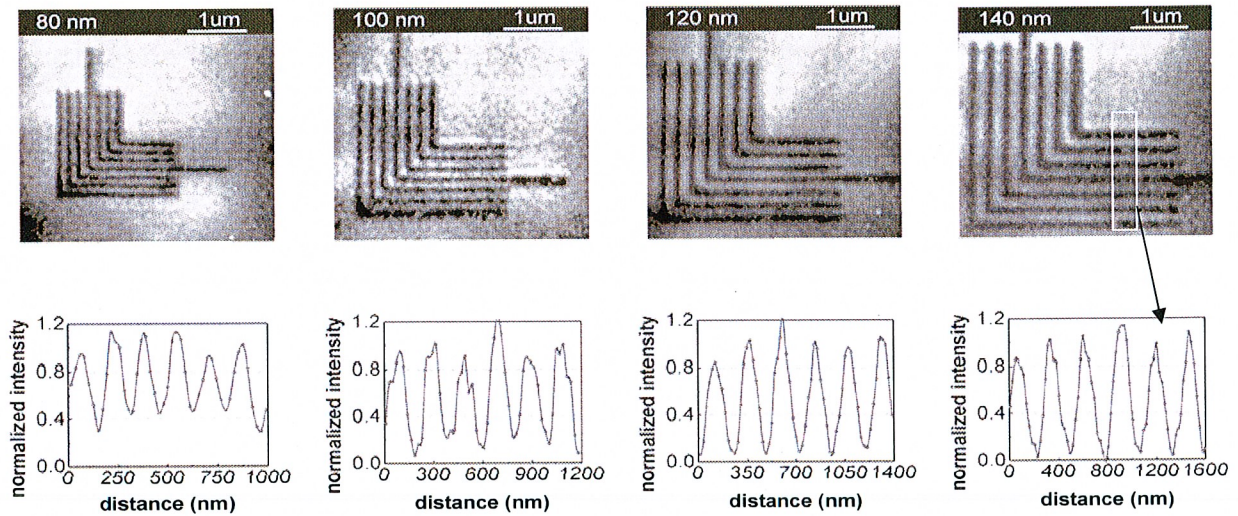
Fig. 9. SXR images and corresponding intensity cross-sections of elbow patterns of (a) 80 nm, (b) 100 nm, (c) 120 nm, and (d) 140 nm half-pitch printed on a Mo/Si multilayer coated mirror. The images were obtained with 5 seconds exposure times. The high modulation of the cross-sections indicate that the features are fully resolved.

Since no smaller grating structures were available at the time of the experiments, the resolution limit of the microscope corresponding to a modulation of 26.5% was evaluated by measuring the 10-90% variation in the intensity in the image of a sharp edge. This analysis yielded a value of 110 nm which was also independently obtained through an image analysis method previously described. [15]To construct the modulation transfer function of the λ=13.2 nm reflection microscope, the results of the grating test and half the value of the knife-edge analysis were combined. This is possible because the illumination conditions of this microscope are practically incoherent as a result of the low spatial coherence of the illumination and the selection of the same objective NA and the condenser NA. These results are plotted in Fig.

10 show the microscope has achieved a spatial resolution, 55 nm, that exceeds the specifications set for the 22 nm technology half-pitch node.
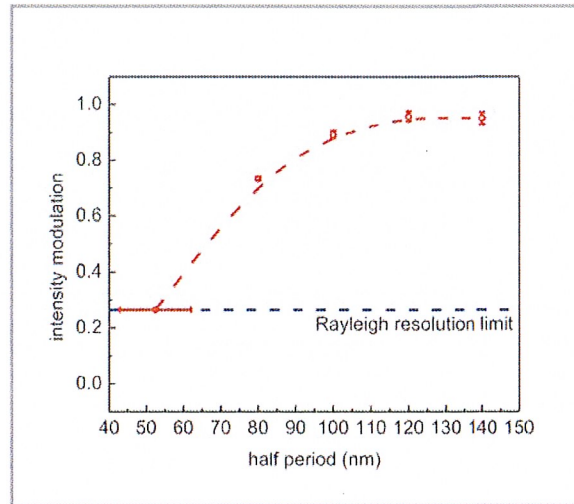
Fig. 10. Measured Modulation Transfer Function (MTF) of the reflection mode microscope. The resolution of the imaging system is ~55 nm.

This first demonstration of a table-top full-field microscope for actinic characterization of EUVL masks opens the path for on-site mask inspection and will contribute to the development of EUV Lithography as a viable technique for the new generation of semiconductor chips. Forecasted improvements in the laser output power are expected to reduce the exposure time to a few seconds.

4. SUMMARY

High average power table-top SXR lasers at Colorado State University have enabled the implementation of compact wavelength scalable microscopes capable to image nanostructures and surfaces with ~ 50 nm spatial resolution.   We have demonstrated a practical microscope operating at λ = 46.9 nm that captures full field images with wavelength resolution and with a single laser shot. This capability will enable tracking of dynamic phenomena in nanoscale systems.   We have also implemented a table-top zone plate microscope at λ =13.2 nm that using a geometry similar to a EUVL stepper images and characterizes absorption defects in EUVL masks with 55nm resolution. This is a first demonstration towards the implementation of a practical defect inspection microscope. Progress in SXR lasers towards increased output power and shorter wavelengths will generate new opportunities for table-top short wavelength microscopy to support nanoscience and nanotechnology.

ACKNOWLEDGMENTS

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