Extreme Ultraviolet Holography with wavelength resolution

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Abstract: Holographic images of carbon nanotubes 50-80 nm in diameter were obtained with a spatial resolution matching the wavelength of the compact capillary discharge extreme ultraviolet (EUV) laser used for illumination, 46.9 nm.

OCIS codes: 140.7240 (UV, EUV, and X-ray lasers), 180.7460 (X-ray microscopy), 340.7480 (X-rays, soft x-rays, extreme ultraviolet (EUV))

1. Introduction

The widespread use of holographic techniques in the extreme ultraviolet and x-ray regions has been largely delayed due to the lack of sufficiently bright compact coherent sources at short wavelengths. Important advances in the field were obtained using synchrotron sources. The first holography demonstration with a soft x-ray laser with a spatial resolution limited to 5 μm was conducted at Lawrence Livermore National Laboratory using a laboratory-size laser facility [1]. The recent development of compact coherent EUV sources with a high degree of spatial coherence has opened new opportunities for the implementation of imaging holographic schemes based on the Gabor geometry with sub-micron spatial resolution [2-4]

In this paper we report the first demonstration of holographic imaging with wavelength resolution using a table-top EUV source consisting of a compact Ne-like Ar capillary discharge laser operating at a wavelength of 46.9 nm [5]. Carbon nano-tubes 50-80 nm in diameter were imaged using a Gabor's in-line configuration. The hologram was recorded in a high resolution photoresist, and digitized using an atomic force microscope. The image was numerically reconstructed with a Fresnel propagator code. Two independent techniques were used to assess the spatial resolution of the image, the standard 10-90% slope knife-edge resolution test and a correlation and convolution method. Both methods yielded a resolution below 50 nm, and practically equal to the wavelength λ = 46.9 nm of the light utilized to record the hologram. The simple and versatile recording method described in this paper opens new possibilities for high resolution imaging of arbitrary shaped objects and might find practical application in biology and material science.

2. Experiment and results

The holograms were recorded with the experimental configuration shown in Figure 1. The test objects were multiple wall carbon nano-tubes (CNT) with an outer diameter between 50 to 80 nm and a length of 10-20 μm deposited on a Si membrane. The sample was prepared by depositing a drop of water with the CNT on the surface of a 100 nm thick Si membrane with a transparency of approximately 25% at λ=46.9 nm. The nano-tubes remained attached to the membrane by van der Waals forces after the water evaporated.

The test object was placed at few microns from a Si wafer spin-coated with a 120 nm thick layer of poly-methyl methacrylate (PMMA) photoresist. The in-line hologram was recorded and after development it was stored as a modulation in the surface of the photoresist. The holograms were digitized into 1024 x 1024 points with a pixel resolution of 9.7 nm by scanning surface of ~10×10 μm^2 with an atomic force microscope.

The digitized holograms were reconstructed numerically. The amplitude and the phase distribution of the field in the image plane was obtained calculating the field emerging from the hologram illuminated by a plane reference wave and back propagating the fields with a Fresnel propagator. Using the image-plane distance of the hologram, the Fresnel free space propagator was evaluated in the spatial frequency domain. The image was generated by taking the two dimensional inverse fast Fourier transform (2D-FFT) of the spatial frequency

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product of the Fresnel propagator and the hologram's 2D-FFT. The digital image of the hologram processed with the Fresnel propagation code generated the reconstructed image shown in Figure 2.

3. Analysis

The reconstructed in-line hologram shown in Figure 2 shows a collection of clearly visible carbon nanotubes. An initial assessment of the image resolution was obtained by line-cuts through the image. Lineouts were obtained in a region where a "plateau" in the maximum and minimum intensities was found to replicate the knife edge resolution test. Taking the 10%-90% rise of the intensity along the lineout yielded an estimate of the spatial resolution of 45.8 ± 1.9 nm.

To obtain a global assessment of the image spatial resolution, a correlation analysis was performed in the reconstructed in-line EUV holograms. This method is based on the correlation between the image and a set of templates of different know resolution generated from the original image. Each of the templates was individually correlated with the original image shown in Figure 2. The resolution of the template that produces the maximum correlation coefficient with the image was assigned as the hologram resolution. The maximum correlation value corresponded to a nano-tube diameter 70.5 nm and a spatial resolution equal to 45.5 nm. The tube diameters obtained from this analysis compare very well with the expected diameter of the nano-tubes used as object (50-80nm normal distribution) and also with the diameters measured with a scanning electron microscope. The resolution obtained by this method is in very good agreement with the value obtained by the direct knife edge test.

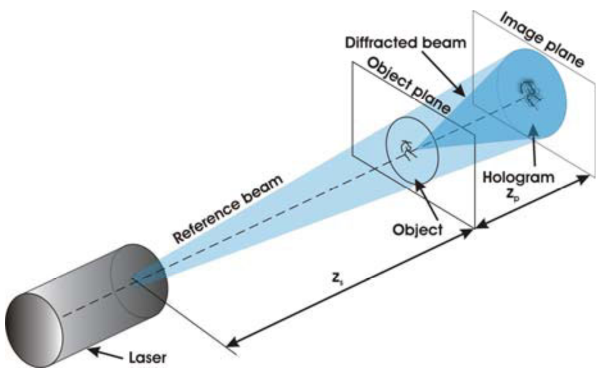

Figure 1: Experimental set up used to record the Gabor's hologram with a table to EUV laser

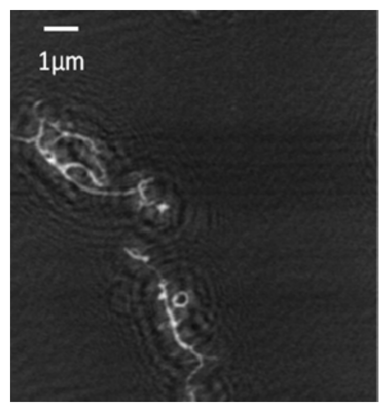

Figure 2: Reconstructed EUV holographic image of 50-80 nm diameter carbon nano-tubes

Work supported by the Engineering Research Centers Program of the National Science Foundation under NSF Award Number EEC-0310717.

References

1. Trebes, J.E., et al., *Demonstration of X-ray holography with an X-ray laser.* Science, 1987. **238**(4826): p. 517-519.
2. Morlens, A.S., et al., *Submicrometer digital in-line holographic microscopy at 32 nm with high-order harmonics.* Optics Letters, 2006. **31**(21): p. 3095-3097.
3. Tobey, R.I., et al., *Ultrafast extreme ultraviolet holography: dynamic monitoring of surface deformation.* Optics Letters, 2007. **32**(3): p. 286-288.
4. Wachulak, P., Bartels, R.,Marconi,M.C.,Menoni,C.S.,Rocca,J.J.,Lu,Y.,Parkinson,B., *Sub 400 nm spatial resolution extreme ultraviolet holography with a table top laser.* Optics Express, 2006. **14**(21): p. 9636-9642.
5. Benware, B.R., et al., *Operation and output pulse characteristics of an extremely compact capillary-discharge tabletop soft-x-ray laser.* Optics Letters, 1997. **22**(11): p. 796-798.