Optics Communications 405 (2017) 312–317

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Imaging properties of an extreme ultraviolet microscope objective with reduced Fresnel number

Mitsunori Toyoda *, Kota Kuramitsu, Mihiro Yanagihara

Institute of Multidisciplinary Research for Advanced Materials, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai, Miyagi, 980-8577, Japan

A R T I C L E I N F O

Keywords:
Soft-X-ray
Schwarzschild objective
Multilayer mirror
Imaging theory

A B S T R A C T

On imaging for full-field extreme ultraviolet microscopy, the Fresnel number on the image plane falls below unity since a high magnification objective remarkably reduces the numerical aperture on the image plane, while the Fresnel number on the object plane is relatively large in most cases. To understand imaging with the high-magnification objective with far different Fresnel numbers on these two planes, in this study, we experimentally confirmed the imaging properties by observing through-focus images of a point object on both the object and image sides. The experiments showed that, the defocus characteristics on the image side were found to be asymmetric with respect to the detector location, while those on the object side were found to be symmetric with respect to the object distance. To explain these unconventional imaging properties, we proposed a simple analytical model considering the two different Fresnel numbers on the high-magnification objective. The model showed that the magnification would vary even if the image plane was within the focal depth, and this yields the asymmetric defocus characteristics. At the same time, when we moved an object along an optical axis, the defocus aberrations were represented by the conventional equation for a large-Fresnel-number system, which can well explain the symmetric defocus characteristics on the object side. We also discuss the effect of an additional phase factor that modifies the amplitude on the image plane.

1. Introduction

On focusing or imaging with a reduced-Fresnel-number lens, it is known that the three-dimensional intensity distribution near the focal point does not coincide with the prediction of the geometrical optics. In its most prominent example, the point of the maximum intensity does not coincide with the geometrical focus even if the aberrations of the lens are well corrected; the position of maximum intensity diverges from the geometric focal point and the intensity profile near the focal point displays an asymmetry along the optical axis [1–3]. The imaging characteristics of this low-Fresnel-number system have been studied by various researchers so far, intended for application to laser focusing optics and cameras that image infinite objects. In these studies, diffraction on the exit pupil to the focal plane was only considered, and the effects of reduced Fresnel number were then discussed.

In order to understand the imaging properties of a full-field microscope, it is necessary to consider two diffractions; from the object plane to the entrance pupil and from the exit pupil to the image plane. On an optical microscope operated in the visible region, the Fresnel numbers on these diffractions are sufficiently larger than unity, so it is not necessary to consider the influence of the reduced Fresnel number. On the other hand, in the extreme ultraviolet (EUV) and soft X-ray region, images of the microscope would be affected as a result of reduced Fresnel number arising from a high magnification of the imaging objective. We shall consider the case of observing fine structures at a spatial scale of a few tens of nanometers using a full-field microscope. Since common two-dimensional detectors for use in the EUV region (i.e., CCD cameras and microchannel plates) have moderate pixel sizes between 10 and 50 μm, the objective should form an enlarged image at high magnifications of ×500 to ×2000 on the detector for observation of fine structures. This high magnification yields a significant decrease of the numerical aperture on the image plane, and as a result, the influence of the reduced Fresnel number should appear on the second diffraction from the exit pupil to the image plane. Conversely, the Fresnel number would be sufficiently large on the first diffraction from the object to the entrance pupil, since the numerical aperture on the object plane is relatively large in most cases. These facts remind us that the imaging properties of the high-magnification objective may differ from those for conventional low-magnification objectives with the large Fresnel

* Corresponding author.
E-mail address: toyoda@tagen.tohoku.ac.jp (M. Toyoda).

http://dx.doi.org/10.1016/j.optcom.2017.08.031
Received 18 February 2017; Received in revised form 13 August 2017; Accepted 14 August 2017

numbers. In this paper, firstly, we experimentally observe point object with a full-field microscope based on the high magnification objective. We report defocus characteristics of the objective by showing through-focus images against both the object and image planes. Next, to explain the experimental results, we propose a simple imaging model for the high-magnification objective, in which different Fresnel numbers are assumed on the two diffractions on imaging.

2. Reduction of Fresnel number in a high-magnification imaging objective

When we apply extreme ultraviolet (EUV) and soft X-rays with wavelengths of 2 to 20 nm to optical microscopy, a high-spatial resolution of a few tens of nanometers can be expected in diffraction-limited imaging. Moreover, as many inner-shell absorption edges of light elements exist in these shorter-wavelength regions, the contrast generated by the difference between their relative absorption coefficients can be used to obtain two-dimensional images of the distributions of light elements. These technical advantages have motivated the development of soft-X-ray and EUV microscopes, which are a new type of optical microscope that can provide video imaging of fine structures on a scale of tens of nanometers in specimens such as living tissues [4,5], magnetic materials [6], and masks for the next-generation lithography [7–9].

To realize EUV and soft-X-ray imaging with high-spatial resolution, high magnification should be required for an imaging objective. A diffractive zone plate is a notable instance of the high-magnification objective [10–12]. Wave diffraction occurring on a concentric grating on a flat transparent membrane can bring imaging under the high magnification. Moreover, by using wave optics theory [13], the zoneplate can be configured to correct a spherical aberration, where blur-free imaging would be expected near the optical axis. On the other hand, it is also known that the zone plate cannot correct off-axis aberrations in the Seidel theory, i.e. coma and astigmatism, since the zone plate does not have a sufficient degree of freedom in its design space to correct these aberrations. Typically, objects several micrometers away from an optical axis would be influenced by the aberrations.

An optical system made of reflective-multilayer mirrors is another instance of an objective with the high magnification. We have recently proposed a novel two-stage imaging objective providing the high magnification of ×1500 and a relatively large numerical aperture (NA) of 0.25 at an operating wavelength of 13.5 nm [14]. This novel objective can be configured to correct the off-axis aberrations to be an anastigmatic system. As image blur for objects several tens of micrometers away from an optical axis can be remarkably low, diffraction-limited imaging would be expected to be possible in a wider field-of-view. We have also demonstrated full-field EUV images of lithography masks with near-diffraction-limited resolution, where fine-test patterns with a structure size down to 30 nm were clearly resolved [15,16].

In developing these objectives, the Fourier-imaging theory is commonly used to describe the imaging performances. For example, in the case of an imaging system under coherent illumination, as shown in Fig. 1(a), the electric fields on the pupil, $\overline{U}(\xi, \eta)$, and the image plane, $U(x, y)$, can be given by [17]

$$\overline{U}(p,q) = \iint o(X,Y) \times \exp\left\{-ik\left(\frac{p}{s_o}X + \frac{q}{s_o}Y\right)\right\} dX dY, \quad (1)$$

$$U(x,y) = \iint \overline{U}(p,q)\, G(p,q) \times \exp\left\{-ik\left(\frac{x}{s_i}p + \frac{y}{s_i}q\right)\right\} dp dq, \quad (2)$$

where $(X,Y), (p,q)$, and (x,y) represent the coordinates on the object, pupil, and image planes, respectively, s_o shows distance between the object and the entrance pupil, while s_i is distance between the exit pupil and the image. o is the amplitude on the object plane, and k is the wave number of light. To simplify the equations, magnification between an entrance and exit pupil is assumed to be unity. The amplitude U on the image plane can be determined by limiting the spatial spectrum $\overline{U}$ of the object o on the pupil by the pupil function G, accounting for the influence of aberration and taking the Fourier transform again. Note that we assume Fraunhofer diffraction in the two diffraction integrations (from the object to the pupil, Eq. (1), and from the pupil to the image plane, Eq. (2)) since the secondary spherical waves arising in the object and pupil planes can be treated as planar waves in Airy disks on the entrance pupil and image plane, respectively.

Table 1
Fresnel number of the Schwarzschild objective with low magnification.

Wavelength (nm)	Object plane	Image plane
13.5	400 000	1900
440	12 000	56

Now, we shall consider the case of increasing the magnification of the optical system while maintaining a constant object–image distance, as shown in Fig. 1(b). As the radius of the Airy disk δ formed on the imaging plane increases, the optical-path difference, d, between the secondary spherical wave generated in the pupil plane and the assumed planar wave simultaneously increases. If d exceeds half the operating wavelength, the secondary spherical wave diffracted on the pupil of radius a can no longer be regarded as a planar wave in the image plane and the approximation introduced in Eq. (2) becomes invalid. The Fresnel number N, which is defined by the following expression, is a useful indicator of whether the planar-wave approximation is applicable [2]:

$$N \equiv \frac{a^2}{\lambda s_i}. \quad (3)$$

Applying the elementary relations $d \cong \delta^2/2s_i$ and $\delta \cong \lambda/\mathrm{NA} = s_i\lambda/a$ to Eq. (3), the Fresnel number is shown in practical form as

$$N = \frac{\lambda/2}{d}. \quad (3')$$

For the planar-wave approximation to hold, d must be suitably smaller than the wavelength, whereas the Fresnel number of the optical system must be greater than unity. Table 1 lists the calculated Fresnel numbers of the typical Schwarzschild objective [18] with a low magnification (magnification: ×50; NA: 0.25; focal length: 20 mm). In the case of the conventional objective with low magnification, the Fresnel numbers of both the object side (corresponding to Eq. (1)) and the image side (corresponding to Eq. (2)) are sufficiently greater than unity and the planar-wave approximation is found to hold well from EUV through visible wavelengths.

To obtain high-spatial resolution with a CCD camera, an EUV microscope must have a high magnification, as mentioned above. Fig. 2 shows a schematic diagram of the novel two-stage objective that we have proposed to realize such a high magnification. This system incorporates an additional concave mirror downstream of the Schwarzschild system and is capable of providing an image magnification of ×5200 with an object–image distance of 2 m. When we apply this high-magnification objective to EUV microscopy, the Fresnel number on the image plane decreases with increasing magnification. Table 2 summarizes the calculated Fresnel numbers for the high-magnification objective at wavelengths of 13.5 and 440 nm, respectively. Even with the high-magnification objective, the Fresnel number remains sufficiently large on the object plane that the planar-wave approximation is valid for diffraction from the object to the pupil. On the other hand, however, the Fresnel number on the image plane is reduced to less than unity due to the increased magnification, indicating that the planar-wave approximation should break down for diffraction from the pupil to the image plane in both the EUV and visible regions.