Compact phase-contrast soft X-ray microscopy

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Abstract. For nearly all elements, the real part, $\delta$, of the complex index of refraction $n (n = 1 - \delta + i\beta)$ is larger than the imaginary part, $\beta$, in the x-ray region. Since only $\beta$ is used in absorption contrast, phase-contrast imaging techniques which give access to $\delta$ are very important. In this paper we present two different implementations of phase contrast in our compact soft x-ray microscope, differential-interference contrast and Zernike phase contrast.

1. Introduction
Different phase-contrast x-ray microscopy methods have been demonstrated at synchrotron light sources. However, the implementation of these techniques in our compact soft x-ray microscope are not straightforward. The main reason is the difference in sample illumination by the condenser or, more precisely, the degree of spatial coherence in the sample plane, which always will be partially coherent. We have simulated the image formation process in a full-field microscope including partial coherence [1]. With the help of this program, different phase-contrast methods have been simulated [2], and the results of the simulation are the basis for two different methods we have verified experimentally. Both techniques are based on the use of diffractive-optical-element (DOE) objectives, i.e., the zone-plate objective is exchanged by a modified optic. Here, one DOE optic gives differential interference contrast (DIC), while the other shows Zernike phase contrast [3, 4]. Both optics are suited for use in compact X-ray microscopes.

The performance of both DIC and Zernike DOE objectives were evaluated in comparison with a normal zone plate by imaging a nickel Siemens star pattern and linear grating test objects. Images obtained with the phase-contrast optics exhibit typical DIC or Zernike contrast enhancement in addition to the normal absorption contrast.

2. Theory
The idea of a single-element phase-contrast optic was first proposed by Chang et al [5]. A similar optic was then used in phase-contrast microscopy by Di Fabrizio [6], and later by Vogt [7] and Chang [8], with a high degree of coherence in the condenser illumination. The latter experiment was carried out by covering parts of the condenser, in order to achieve circular polarized radiation. Since then, other types of single-element phase-contrast optics have been developed and tested [9, 10]. In compact soft X-ray microscopy, the degree of coherence in the sample plane is low due to the photon economy and thus new types of optics were developed to satisfy this constraint.

The Zernike DOE and the DIC-DOE are similar in the way they manipulate the optical field since both optics make a type of filtering in the Fourier plane. However, the contrast effect is fundamentally
different. Whereas the Zernike DOE phase-shifts the undiffracted field relative to the diffracted field by $\pm \pi/2$ yielding contrast for phase-contributing parts of an object, the DIC-DOE creates a point-spread function (PSF) with two spots. These spots have a certain separation, called the shear, and a phase difference, called the bias. The shear and the bias are important parameters in achieving the phase-contrast effect.

2.1. Single-element Zernike phase-contrast optic
Zernike phase contrast is an established technique in x-ray microscopy when using an arrangement where a phase ring phase-shifts the undiffracted light [11, 12]. However, in soft x-ray microscopy, focal lengths are short which makes a phase ring more difficult to implement. By moving the phase-shifting ring to the zone-plate itself and instead shifting the appropriate zones, the arrangement is simplified. The result can be viewed in figure 1.c. It is important to emphasize that this is only possible if the Fourier plane and the zone plate plane are comparable. This will affect the available field-of-view depending on how coherent the illumination of the sample is.

With Zernike phase contrast, one may either phase-shift the diffracted light by $\pi/2$ (positive Zernike phase contrast) or $-\pi/2$ (negative phase contrast). For X-rays, the positive Zernike configuration results in an inverted contrast of the sample, as compared to absorption contrast.

2.2. Differential-interference contrast optic
In a previous publication, the illumination requirements for single-element DIC imaging were thoroughly investigated [2]. It can be shown that by making a so-called phase cut in the optical element, a PSF with two spots can be created. The shear and the bias of the resulting PSF depend on the position of the phase cut, which phase shifts the zones on one side by $\pi$ (see figure 1.a). It can also be shown that a useful position of this phase cut is at half the radius of the zone plate, creating the side-cut DIC-DOE. This position yields a shear equal to the resolution limit of the optic, and a bias of $\pi/3$. Due to the small shear produced, this optic does not degrade the resolution.

A necessary requirement for the side-cut DIC-DOE is to have a sufficient degree of coherence in the sample plane. The shear distance in the sample plane needs to be coherently illuminated. If this is fulfilled, two points in the sample plane that are separated by the shear can interfere in the image plane. If the degree of coherence is partially coherent over the shear, the image contrast will decrease.

![Figure 1](image)

**Figure 1.** (a) The DIC-DOE, (b) a normal zone plate and (c) the Zernike zone plate.

3. Results
Each type of phase-contrast DOE was manufactured in nickel [13]. The outermost zone was 50 nm and the diameter was 50 or 75 µm. The resulting image for each phase-contrast optic was compared to an equivalent zone plate without any phase shifts. The imaged objects were also manufactured in nickel, with a thickness of approximately 100 nm.

Figure 2 shows images taken with the compact soft X-ray microscope using the two types of phase-contrast DOEs and a corresponding normal zone plate. The wavelength was 2.48 nm and the condenser had an outermost zone width of 50 nm and a diameter of 4.53 mm. The resulting numerical aperture ratio was $m=0.5$ which was enough to give sufficient degree of coherence in the sample...
plane. When compared to an equivalent zone plate without any phase shifts, both optics yielded a measurable contrast increase for the given object [3, 4]. In addition, the Zernike zone plate showed inverted contrast as expected for the positive Zernike configuration. Although not visible in figure 2, the field-of-view was limited in the Zernike contrast arrangement. This is a consequence of integrating the phase plate with the zone plate, but depends on the divergence of the illumination. The Zernike contrast image also suffered from halo and shade-off effects, which are known artifacts from optical microscopy.

![Figure 2](image-url) Images taken in the compact soft x-ray microscope using (a) a side-cut DIC-DOE, (b) a normal zone plate, and (c) a Zernike zone plate. Phase-contrast effects are clearly visible in (a) and (c), where contrast reversal is also visible. Note the difference in scale between (b) and (c).

4. Conclusions
Compact soft x-ray microscopy can benefit from single-element phase-contrast optics since implementation and design is straightforward. Contrast increase is possible, resulting in a lower absorbed dose and/or reduced exposure times. The Zernike zone plate has the advantage of improved contrast in all directions, while it is limited in field-of-view. The DIC-DOE can provide a larger field-of-view but will only show contrast in one direction. Further investigation in the benefits and disadvantages of each optic is necessary before choosing one above the other.

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