Ronchi test for characterization of nanofocusing optics at a hard x-ray free-electron laser

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We demonstrate the use of the classical Ronchi test to characterize aberrations in focusing optics at a hard x-ray free-electron laser. A grating is placed close to the focus and the interference between the different orders after the grating is observed in the far field. Any aberrations in the beam or the optics will distort the interference fringes. The method is simple to implement and can provide single-shot information about the focusing quality. We used the Ronchi test to measure the aberrations in a nanofocusing Fresnel zone plate at the Linac Coherent Light Source at 8.194 keV. © 2012 Optical Society of America

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Hard x-ray free-electron lasers (XFELs) are new and powerful sources of coherent x-rays. The advent of these sources has enabled a variety of groundbreaking and exciting scientific experiments [1]. XFEL radiation is unique in providing short hard x-ray pulses in the femtosecond regime with high peak power and good longitudinal and transverse coherence. Thanks to the coherence it is possible to focus the beam to small dimensions, which is required in many experiments [2]. Typical spot sizes are in the range from a few micrometers down to 100 nm or less. For hard x-rays there exist a number of different focusing optics to choose from, of which Kirkpatrick–Baez mirrors, diffractive Fresnel zone plates, and compound refractive lenses are among the most widely used. The characterization of these optics is often crucial for the proper interpretation of experimental results.

At synchrotron sources this is traditionally done by scanning a knife edge or a wire through the focal plane. Alternatively, a fine test structure can be scanned in a scanning x-ray microscopy scheme. More recent techniques use the coherent diffraction pattern created by a test structure placed in, or nearby, the focus, and an iterative phase-retrieval algorithm to recover the full complex wavefield after the optic [3,4].

At XFELs the measurement of the focus is complicated because the intensity in the focus is often high enough to damage any test structure. Further difficulties arise from pulse-to-pulse intensity fluctuations of present XFELs. However, the fact that the focused beam can damage a sample has been exploited to measure the focus shape by recording a series of imprints in a flat substrate at varying fluence levels [5]. This technique is routinely used to characterize focused beams at XFELs, but since the imprint sample has to be removed from the experimental chamber for analysis it cannot give direct feedback of the focusing properties during an experiment. The same is also true for most iterative-based coherent diffraction methods where the reconstruction can be a tedious procedure.

In this Letter we describe the use of the classical Ronchi test [6] for aberration characterization of a nanofocusing optic at the Linac Coherent Light Source (LCLS). The Ronchi test is an interferometric method that was invented already in the 1920s to investigate the aberrations of curved mirrors. Since then it has been widely used in the field of visible optics metrology. The basic principle is the following (see Fig. 1): A grating is placed close to the focal plane of an optical system, and a detector is placed further downstream. The different diffraction orders, (more specifically the zeroth order and the two first orders) can then interfere with each other, giving rise to a characteristic fringe pattern, the so-called Ronchigram. The pattern normally consists of straight fringes that will be deformed if aberrations are present. These aberrations give rise to very characteristic fringe deformations. An excellent overview of the method and pictures of different Ronchigrams can be found in [7].

The experiment was performed at the Matter in Extreme Conditions (MEC) instrument at LCLS. The focusing optic under investigation was a 0.5 μm thick

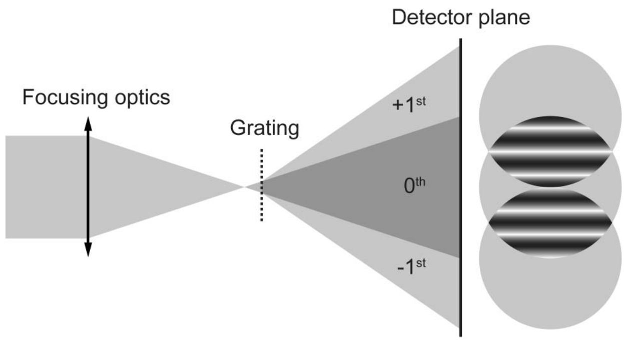

Fig. 1. Experimental arrangement for the Ronchi test. Hard x-rays (8.194 keV) from LCLS are focused by a zone plate. A grating is placed close to the focus, generating several identical but shifted copies of the incident spherical wave. The resulting interference fringes from the overlapping zeroth and first orders are recorded with a two-dimensional x-ray detector.

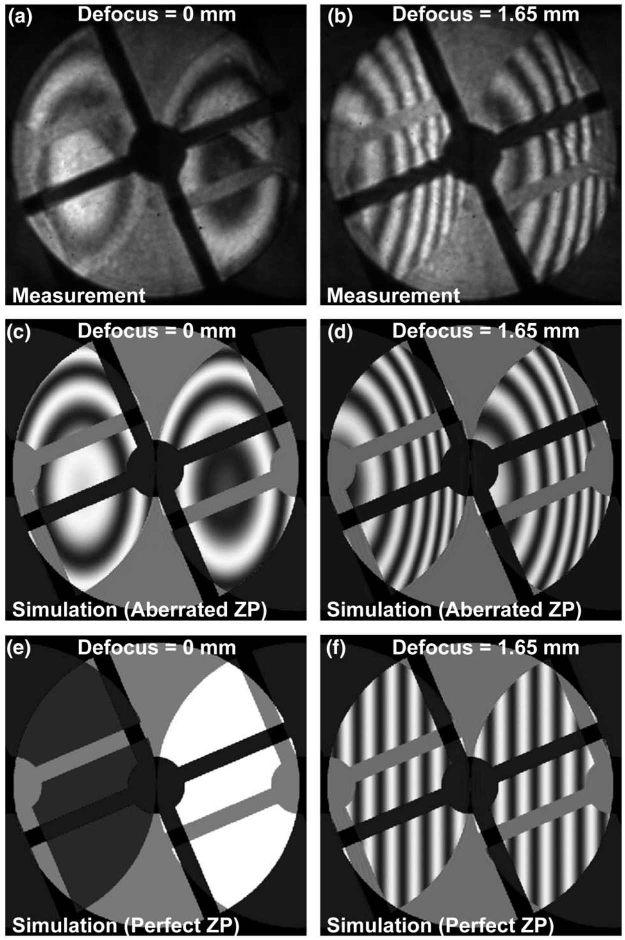

Fig. 2. Comparison between measured and simulated Ronchigrams. Top row: measured images for two different grating positions. Middle row: simulated images with aberrations present. Bottom row: simulated images for an aberration-free optic. The dark middle circle and cross structure is the zone-plate central stop.

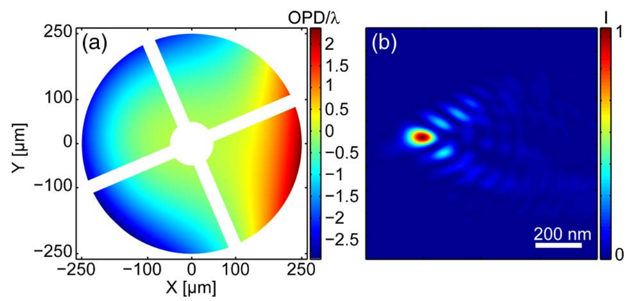

Fig. 3. (Color online) (a) Simulated OPD in the lens plane. (b) Intensity in the plane perpendicular to the optical axis with the highest intensity.

tungsten zone plate with a diameter of 500 μm, an outermost zone width of 100 nm, and a focal length of 334 mm at the used 8.194 keV photon energy. To ensure sufficient longitudinal coherence a Si monochromator was inserted after the undulator. A combination of a 100 μm diameter central stop and a 20 μm diameter order-sorting aperture removed undesired diffraction orders from the zone plate.

The Ronchi grating was made of diamond [8] and had a thickness of 1.5 μm with an additional layer of 250 nm tungsten on top, giving a first-order diffraction efficiency of roughly 13%. A grating period of 200 nm matches the numerical aperture of the focusing zone plate, ensuring optimum overlap of the zeroth and first orders as in Fig. 1. The resulting interference patterns were recorded on a Princeton Instruments PIXIS-XF 2048B fiber-coupled phosphor camera positioned 4 m after the focus. A single XFEL pulse contained enough photons to produce a Ronchigram with good signal level and contrast. At the same time the intensity on the grating was low enough to not damage it during the experiment. However, the method also works at higher intensities that potentially destroy the grating since a Ronchigram can be captured before damage occurs.

Images were recorded at different focus-to-grating distances, and Figs. 2(a) and 2(b) show the measured single-shot Ronchigrams. By looking at the straightness of the interference fringes in Fig. 2(b), it is directly evident that the zone plate is not aberration-free. An aberration-free optic should give the pattern shown in Fig. 2(f). Moreover, when the grating is placed in focus [Fig. 2(a)] a perfect optic would produce a zero-fringe pattern, as in Fig. 2(e). From the characteristic ellipsoidal fringe pattern it can be concluded that the zone plate suffers from coma at 90° to the direction of the grating lines. The slight shift of the pattern in the downward direction of the image indicates the presence of astigmatism in a direction close to the grating direction. In order to further quantify the aberrations, simulations were performed where aberrations were added in a systematic fashion to find the best agreement with the measured data. The resulting optical path difference (OPD) in the zone plate plane is shown in Fig. 3(a), and the simulated Ronchigrams are shown in Figs. 2(c) and 2(d). The OPD is a sum of coma at 90° with a peak error of 2λ and astigmatism at 10° with a peak error of 1.8λ (0° is along the grating lines). Figure 3(b) shows the simulated beam shape in the plane with the highest intensity, and a typical coma tail is evident. The observed aberrations can be a combination of distortions in the LCLS beam, caused by upstream mirrors, and actual aberrations in the zone plate. However, the expected LCLS beam aberrations are much smaller than the measured aberrations [9]. Therefore it is most likely that the zone plate is the main source of wavefront errors. These errors were probably caused by zone misplacements during zone-plate fabrication due to thermal drift and electron-beam deflection aberrations in the relatively long e-beam lithography process step.

At this point it is important to note the following. To begin with, one should ideally record two Ronchigrams with perpendicular grating orientations; this is necessary because if only one direction is used, it is not possible to detect astigmatism that is oriented in the same direction as the grating lines. This is probably most easily implemented by rotating the grating 90° or fabricating a test target with two closely positioned gratings with different orientations allowing for easy change between the two gratings. An alternative is to use a two-dimensional (2D) grating or chessboard pattern, which will give information in two directions simultaneously [10]. However, doing so will generally give more complicated interference patterns since more than two orders are overlapping, making direct visual interpretation harder. For these cases one might have to rely on methods such as Fourier filtering of images to isolate different orders [11]. It is also interesting to note that the Ronchi test is essentially a form of shearing interferometer [12]. Shearing interferometers have found widespread use in the hard x-ray region as phase-contrast imaging devices and wavefront sensors, and recently a shearing interferometer was used to measure the wavefront from the LCLS [9]. The majority of these methods use gratings or 2D structures with periods in the micrometer range, giving a small shear, and rely on the Talbot self-imaging of the gratings.

The Ronchi test described in this Letter distinguishes itself by the use of gratings with much smaller periods. Thankfully, the grating does not have to be fully absorbing, which is difficult to achieve at small periods. Optimal contrast in the interference pattern is achieved when the zeroth order and the first orders have equal intensity. As an example, for tungsten used at 8.194 keV this is achieved at a thickness of 1 μm, which is within current nanofabrication capabilities. However, also gratings with lower efficiency, such as the one used in this experiment, can produce sufficient contrast.

The transverse coherence of the XFEL beam eliminates the need for a source grating as used in the original visible-light experiments with incoherent light sources. The method in its simplest implementation therefore only requires a single optical component, namely the Ronchi grating, and since the grating is placed close to the focus, where the beam is small, it does not have to be large. Like most other interferometric techniques, the method is sensitive to vibrations. However, this is not an issue at XFEL sources since the Ronchigrams can be recorded in a single pulse. Moreover, the method does not impose any specific requirements on the detector. The contrast in the interference fringes is good and the divergent geometry makes it easy to resolve the patterns. In addition, the number of fringes on the detector is easily adjustable by moving the grating closer to or further away from the focus.

The main benefits of the Ronchi test are the easy implementation and the straight-forward visual interpretation of the Ronchigrams. If one observes perfectly straight fringes, the optic has no aberrations in the direction perpendicular to the grating direction and should perform according to the diffraction limit. No further analysis in needed. The method is ideally suited for XFEL sources where it can be used to monitor the performance of focusing optics on a single-shot basis.

In conclusion, we have demonstrated the applicability of the classical Ronchi test for characterization of nanofocusing optics at an XFEL source. We used the method to measure the aberrations in a zone plate focusing hard x-rays at the LCLS. The method should also be useful for nanobeams at synchrotron sources, where it can be used to quickly check the performance of focusing optics before, during, and after experiments.

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