Materials for x-ray refractive lenses minimizing wavefront distortions

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X-ray lens machining methods and employed materials

An overview of previously and currently used x-ray lenses, ordered by manufacturing technique, is presented in **Table I**.

Characterization methods for x-ray lenses

The lens shape and its homogeneity can be analyzed conveniently and nondestructively at-wavelength (i.e., with x-rays). Optical methods, however, are better suited to study surface roughness.

X-ray methods

Grating interferometry—Grating interferometry directly reveals the effect of the lens on the phase of the transmitted x-ray wavefront. Improper focusing due to aberrations or density variations thereby becomes visible. Grating interferometry is usually employed using a phase grating and an analyzer grating[48,49] that is translated in small steps in front of a lower-resolution camera. For large aperture lenses, the resolution of an x-ray camera is sufficient without the help of an absorbing analyzer grating.[50] The method is limited to weakly focusing lenses.

Near-field speckle tracking—Shifts in the position of a near-field speckle pattern created by a random phase object in a coherent beam occur when an x-ray lens is placed into the beam. The displacement field allows the calculation of the phase shift of the lens as a function of beam position, so the shape of the lens can be recovered.[51]

Ronchi test—The Ronchi test is an interferometric method requiring a grating to be placed close to the focal plane after an x-ray lens. The ± first and zero-order diffracted beams interfere in the detector plane, yielding a Ronchigram.[52] The acquired image is analyzed for distortions that can be compared to simulated lenses featuring shape imperfections. This is useful for x-ray free-electron lasers, as it needs only a single exposure per orientation (vertical or horizontal).

Ptychography—Ptychography is a method based on coherent diffraction that evaluates the effect of the lens shape and homogeneity on the x-ray wavefront.[53] A coherent x-ray beam of a limited cross section is scanned over a test sample (e.g., a Siemens star comprised of nano- and micrometer-sized radial spokes), in such a way that neighboring scan points have sufficient overlap. The different diffraction patterns share redundant information so that phase retrieval can be achieved iteratively and the illumination function is recovered. The illumination function represents the phase and amplitude of the focused beam, and thus contains information on the x-ray lens.

X-ray tomography—Standard x-ray tomography of a two-dimensional (2D) lens inside its highly absorbing encapsulating container leads to noisy projection images in a significant rotation angle range, causing failure in attempts at tomographic reconstruction. The lenses can be imaged properly when removed from their container.[54] **X-ray laminography** can be employed on encapsulated 2D lenses[55] and possibly on planar lenses. Information such as on inclusions and oxidized grain boundaries in Be lenses of different grades can be obtained.

Small-angle x-ray scattering (SAXS)—Inhomogeneities inside the lens material are electron density variations that give rise to SAXS intensity. Rough interfaces between grains, voids, and inclusions participate in this scattering. Different material classes give different strengths of the SAXS signal; single-crystalline materials yield the smallest SAXS signal. Various lens materials have been tested for their SAXS signal.[2,55]

Other methods

Scanning electron microscopy is a tool for the investigation of planar one-dimensional lenses, especially for measuring the apex radius and width. Production errors such as shape variation over depth can be visualized (e.g., the common undercut or the tapering of side walls) during the etching process.[56]

White-light interferometry[57,58] and **confocal microscopy** are capable of measuring the height profile of each lens side, as long as the local slope is not too high and the reflected light reenters the optical system. The surface roughness can be measured close to the apex.

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