COHERENT HARD X-RAY FOCUSING OPTICS AND APPLICATIONS

Re

W.B. Yun, P. J. Viccaro, J. Chrzas, and B. Lai

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Argonne National Laboratory, Advanced Photon Source

9700 S. Cass Ave., Argonne, IL 60439

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Abstract

Coherent hard x-ray beams with a flux exceeding 10^9 photons/second with a bandwidth of 0.1% will be provided by the undulator at the third generation synchrotron radiation sources such as APS, ESRF, and Spring-8. The availability of such high flux coherent x-ray beams offers excellent opportunities for extending the coherence-based techniques developed in the visible and soft x-ray part of the electromagnetic spectrum to the hard x-rays. These x-ray techniques (e.g., diffraction limited microfocusing, holography, interferometry, phase contrast imaging and signal enhancement), may offer substantial advantages over non-coherence-based x-ray techniques currently used. For example, the signal enhancement technique may be used to enhance an anomalous x-ray or magnetic x-ray scattering signal by several orders of magnitude. Coherent x-rays can be focused to a very small (diffraction-limited) spot size, thus allowing high spatial resolution microprobes to be constructed. The paper will discuss the feasibility of the extension of some coherence-based techniques to the hard x-ray range and the significant progress that has been made in the development of diffraction-limited focusing optics. Specific experimental results for a transmission Fresnel phase zone plate that can focus 8.2 keV x-rays to a spot size of about 2 microns will be briefly discussed. The comparison of measured focusing efficiency of the zone plate with that calculated will be made. Some specific applications of zone plates as coherent x-ray optics will be discussed.

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Introduction

A radiation source with adequate coherent power offers the unique capability of studying both the amplitude and the phase distribution of a signal wave by detecting its interference with another mutually coherent wave whose wavefront is known.¹ Techniques based on this coherence property have made a significant impact in science and technology, as well as in our daily life with the invention of the optical laser and the development of necessary coherent optics. The construction of the third generation synchrotron x-ray sources worldwide (such as the Advanced Photon Source) will provide many orders of more coherent x ray flux than that from currently available the most brilliant x-ray sources.² The prospect of such high power coherent x-ray sources opens up excellent opportunities for extending the coherence-based techniques developed in the visible part of the electromagnetic spectrum to the x-ray spectral regime. Concurrently, rapid advances in the last decade in microfabrication technology, high precision surface finishing, crystal growth, controlled layer deposition, and precision metrology have made it possible to overcome some stringent requirements for making coherent x-ray optics.³ Those advances have allowed for extraordinarily rapid development in soft x-ray holography, micro-imaging, micro-analysis, and microspectroscopy.⁴⁻⁶

With the availability of the high coherent x-ray flux that will be provided by the third generation synchrotron sources, it becomes increasingly important to develop coherent x-ray optics for hard x-ray applications to extend the experiments currently conducted in the soft x-ray regime to the hard x-ray regime. Such an extension will provide excellent new capabilities that are not available in the soft x-ray regime, such as increased absorption length and increased fluorescence yield. In addition to this extension, some coherence-based techniques that have not yet been applied to the

x-ray spectral region can be developed, e.g., coherence-based signal enhancement, which is well developed in the visible light region. The principle of this technique is that the interference intensity of two mutually coherent beams can be many orders of magnitude larger than that of the signal itself. The dependence of interference on polarization can be used to enhance or depress certain polarization components of the signal wave by adjusting the polarization and phase of a mutually coherent reference beam. This signal enhancement principle can be applied to a broad range of x-ray techniques. For example, an x-ray scattering signal from the magnetic moment of a scattering system may be enhanced by several orders of magnitude. Such an enhancement could greatly increase the usefulness of magnetic x-ray scattering for materials research. Successful implementation of those coherence-based techniques requires that suitable coherent x-ray optics be developed. In this paper, we shall limit our discussion to Fresnel zone plates for hard x-ray applications and their applications as coherent x-ray optics.

Fresnel zone plates

Fresnel zone plates have been known more than 100 years.⁷ Their use as an important microfocusing device in the x-ray spectral region ($0.5 \text{ \AA} < \lambda < 100 \text{ \AA}$) was established in recent years. A Fresnel zone plate consists of circular zones of materials having alternating optical refractive indexes. Geometrical configuration of the zones in a zone plate is similar to that of interference fringes of a hologram of two mutually coherent point sources.⁸ The radial position R_K of the K th zone is given by $R_K^2 = Kf\lambda + K^2\lambda^2/4$, where λ is the wavelength of radiation and f the focal length of the zone plate. The equation can be approximated as

$$R_K^2 = Kf\lambda , \quad (1)$$

without spherical aberration if the maximum zone index K_{max} satisfies $K_{max} < (2f/\lambda)^{1/2}$.⁹ This condition is easily met by most x-ray zone plates fabricated thus far and Eq. (1) will be used as the zone plate equation in this paper.

The transmittance of a zone plate described by Eq. (1), which characterizes the modification to the wave front of an incident beam, is periodic in $r^2 = x^2 + y^2$ space, and the period is $2f\lambda$. The transmittance function of the zone plate $T(r)$, therefore can be expanded in a Fourier series of the form¹⁰

$$T(r) = \sum C_N \psi(r; -N/f), \quad (2)$$

where $\psi(r, -N/f) = \exp[-jN\pi r^2/f\lambda]$ represents a spherical wave converging to the Nth-order focus of the zone plate, and $j = \sqrt{-1}$.

The focusing efficiency of a zone plate, defined as the percentage of radiation delivered to the nth order focus, is equal to the absolute square of the Fourier transform coefficient $C_N = 1/2f\lambda \int T(r) \exp[-jN\pi r^2/f\lambda] dr$. For a zone plate with a square zone profile and thickness d , the focusing efficiency of the Nth order focus η_N is¹¹

$$\eta_N = \begin{cases} 1/4 & N = 0 \\ (\gamma_1^2 + \gamma_2^2 - 2\gamma_1\gamma_2 \cos(2\pi d(\delta_2 - \delta_1)/\lambda)) / (N\pi)^2 & N = \text{odd} \\ 0 & \text{otherwise,} \end{cases} \quad (3)$$

where $\gamma_i = \exp(-2\pi d\beta_i/\lambda)$, and β_i and δ_i are imaginary and real parts of the refractive indexes of two neighboring zones $n_i = 1 - \delta_i - j\beta_i$, $i = 1, 2$.

Figure 1 shows the focusing efficiency of the first order focus ($N = 1$) calculated using Eq. (3) as a function of x-ray energy and thickness of a zone plate consisting of

alternating Cu and Al zones. Note that focusing efficiency better than 10% may be obtained for the x-ray energies calculated, and focusing efficiency as high as 40% may be obtained for the high-energy end of the x-ray spectrum if the thickness of the zone plate is properly made.

Currently, there are essentially two types of microfabrication techniques developed for producing Fresnel zone plates for x-ray applications: the lithography-based techniques¹² and the sputtering/slicing techniques.¹³ The lithography-based fabrication techniques use an either electron beam writer or deep UV holography to generate a zone plate pattern and, subsequently, transfer the pattern into a zone plate. The techniques have been used for producing zone plates of spatial resolution as small as 450 Angstroms.¹⁴ The usage of these zone plates has been limited to x-rays of energies less than 1 keV, as their thickness is generally too small to modify the wave front of a hard x-ray beam to achieve an adequate focusing effect. Currently, it seems possible to fabricate microstructures of 5:1 aspect ratio, which is defined as the ratio of the thickness of the microstructure to the smallest feature size in the microstructure. It is, therefore, in principle possible to use the lithography-based technique to produce a zone plate of a spatial resolution about 0.2 micron for x-rays of energies up to 20 keV (see Fig. 2), as the spatial resolution of the zone plate is roughly equal to the smallest zone width. The sputtering/slicing technique was primarily developed for hard x-ray focusing applications. While fairly thick zone plates can be fabricated by this technique for focusing high energy x-rays, it is not easy to make thin zone plates for applications for low energy x-rays due to the grinding/polishing process involved. It is reasonable to expect that the development of the two types of fabrication techniques will eventually overlap and, thus, zone plates applicable to a large x-ray energy range can be fabricated.

Recently a zone plate consisting of alternating Al and Cu zones fabricated by Dr. R. Bionta and his group using the sputtering/slicing technique was characterized using a synchrotron bending magnet source.¹⁵ The primary focal length of the zone plate is 40 cm for 8.0 keV x-rays. Both spatial resolution for focusing 8.2 keV x-rays and focusing efficiency as a function of x-ray energy were measured. The measured focusing efficiency is shown in Fig. 3. The focusing properties of the first, second, and third order foci were studied. The focus spot size of the third order focus is less than 2×4 micron, as evidenced by the gold grid image obtained (see Fig. 4). The spot sizes of the second and first order focus are about 1.5 and 3 times that of the third order focus, respectively. The focal spot size of the first order focus is significantly larger than the smallest zone width (0.19 micron) of the zone plate primarily because of inadequate spatial coherence in the illumination beam. The focal spot size is mainly determined by the geometric demagnification of the x-ray source size at the storage ring and the full width half maximum 300×700 microns, which is essentially the electron beam size at the bending magnet point. Our experimental setup corresponds to a demagnification factor of about 55 and, thus, the demagnified image of the source at the third order focus would be 1.8×4.2 microns, in agreement with the measured results. The fact that the measured focal spot size is comparable to that calculated from simple geometric demagnification of the source indicates that the zone plate can focus x-rays to a spot much less than 2×4 microns.

Some applications as coherent x-ray optics

Fresnel zone plates are among the most important coherent x-ray optics to be used in coherence-based x-ray techniques. The symmetry about the focusing axis of a focused beam and the lack of spherical aberration (as discussed in the last section) may make zone plates the optics of choice for producing a high quality spherical x-

ray wave. This wave-front-shaping capability is very useful in coherence-based x-ray techniques, e.g., x-ray holography and interferometry. This capability was, in fact, used in a Fourier transform holography technique using soft x-rays emitted from a low energy x-ray undulator.¹⁶ The technique can be extended to the hard x-rays region with the hard x-ray undulators to be installed on the third generation storage rings that are under construction worldwide.

The wave-front-shaping capability may also be used to manipulate the wave front of a coherent x-ray beam. A coherent plane wave can be focused to a small spatial area at the expense of increased beam divergence. This is useful for applications where a small sample needs to be illuminated by a large amount of coherent photons while large divergence in the illumination beam is acceptable. Combination of a short focal length and a long focal length zone plates can be used to built a beam expander, just as two lenses are used in visible lighth region to increase or decrease a beam size.

The wavefront of a coherent wave is well defined and thus diffraction-limited focusing can be obtained with diffraction-limited optics. The high coherent flux from the third generation x-ray sources permits one to focus x-rays to a small spot with a large flux of x-ray photons at the focal point. Thus, high spatial resolution microprobes can be constructed. The x-ray wavelength is about 3 orders of magnitude shorter than that of visible light, and so samples can be imaged or probed with a spatial resolution far better than that obtainable with visible light. The combination of the small focal spot, the moderate x-ray interaction cross section with matter, the contrast mechanism using absorption edges, and elemental sensitivity (labeled by characteristic fluorescence x rays) will provide excellent opportunities in structural and materials analysis. For example, x-ray phase contrast microscopy similar to that in the visible light regime can also be developed by properly using a

phase shifter.¹⁷ In the x-ray spectral region, the real part of the atomic scattering factor is generally larger than its imaginary counterpart. As a consequence, phase contrast arising from elemental composition and their spatial distribution in a sample may provide a better contrast for imaging than absorption-based contrast. This phase contrast can be further enhanced by interfering with a coherent reference beam. The increase in contrast not only increases the signal-to-noise ratio, but also reduces the radiation damage to the sample, which is of great importance in biological applications where radiation damage is a serious concern.⁵

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Figure Captions

Fig. 1 The focusing efficiency of the first order focus ($N = 1$) calculated using expression (4) as a function of x-ray energy and thickness of a zone plate consisting of alternating Cu and Al zones.

Fig. 2 The focusing efficiency of the first order focus ($N = 1$) calculated using expression (4) as a function of x-ray energy and thickness of a free-standing fold zone plate.

Fig. 3 Measured focusing efficiency of a Al/Cu zone plate as a function of x-ray energy. The solid line is calculated focusing efficiency using expression (4) assuming that the zone plate thickness is 18 micron.

Fig. 4 X-ray transmission image of a square gold grid (6 micron wires on a 25 micron spacing). The image was obtained by scanning the grid across the third order focus of the zone plate and the x-ray energy was 8.2 keV. Each pixel presents a 1 micron step in the scan.

Gold zone plate

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10 μm