Bragg Magnifier: High-efficiency, High-resolution X-ray Detector

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Abstract. X-ray computer microtomography is a powerful tool for non-destructive examinations in medicine, biology, and material sciences. The resolution of the presently used detector systems is restricted by scintillator properties, optical light transfer, and charge-coupled-device (CCD) granularity, which impose a practical limit of about one micrometer spatial resolution at detector efficiencies of a few percent. A recently developed detector, called Bragg Magnifier, achieves a breakthrough in this respect, satisfying the research requirements of an efficient advance towards the submicron range. The Bragg Magnifier uses the properties of asymmetric Bragg diffraction to increase the cross section of the diffracted X-ray beam. Magnifications up to 100x100 can be achieved even at hard X-rays energies (>20 keV). In this way the influence of the detector resolution can be reduced accordingly and the efficiency increased. Such a device has been developed and successfully integrated into the Tomography Station of the Materials Science Beamline of the Swiss Light Source (SLS). The device can be operated at energies ranging from 17.5 keV up to 22.75 keV, reaching theoretical pixel sizes of 140 nm.

Keywords: X-ray imaging, synchrotron microtomography, asymmetric Bragg diffraction

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INTRODUCTION

The combination of X-ray microscopy with tomographic techniques as well as the exceptional properties of third-generation synchrotron radiation sources allow to obtain volumetric information of a specimen at micron or sub-micron scale with minimal sample preparation. Microtomographic investigations tend nowadays towards the analysis of millimeter-sized specimens at micrometer resolution within minutes. The requirements on the detectors in terms of spatial resolution and efficiency are therefore very high and tremendous efforts have been made all over the world. The most established detection method consists of converting X-rays into visible light with a scintillator and projecting them onto a charge coupled device (CCD) with the help of suitable optics [1, 2, 3]. It has been shown that the spatial resolution of the visible-light-based approach is intrinsically limited to about $1\text{ }\mu\text{m}$ by scintillation properties, optics efficiency and CCD granularity [4]. Different approaches have been proposed for efficiently exceed the micrometer barrier: Fresnel zone plates [5, 6, 7, 8], parabolic compound refractive lenses [9] and Kirkpatrick-Baez setups [10] have demonstrated to reach submicrometer resolution with sufficient efficiency but with a limited field of view. This article describes a device, called Bragg magnifier, which achieves a breakthrough in this respect, satisfying the requirements for efficient imaging at submicron resolution at high energies. The new instrumentation, inspired by the setup of Kuryiama *et al.* [11], performs two dimensional magnification in the hard X-rays regime ($> 20\text{keV}$) exploiting the well-known principle of asymmetrical Bragg diffraction from two crossed flat crystals: for the prototype described in this work, a pair of Si(220) crystals with an asymmetrical cut of 8° has been used. If the incoming divergence of the beam is kept sufficiently small ($< 20\text{ }\mu\text{rad}$) then a comparison with the relevant rocking curve implies that the first Si(220) crystal accepts 95% of the incoming intensity, which means that almost no flux is lost when passing through the crystals. The magnifying optics collect the intensity distribution of the incoming beam, which contains absorption and phase information about the sample, and magnifies it, acting therefore as a full field microscope. The enlarged image can be converted to visible light in a much more efficient way (thicker scintillator) since the larger spread will be compensated by the X-ray magnification. As a consequence, the efficiency will be enhanced *without* deterring the spatial resolution.

FIGURE 1. (a) Functional principle of the Bragg magnifier depicting both crystals, the object and the image (detector) planes. "r" describes the incident beam coordinates, "d" the diffracted one. The inset shows the principle of coplanar asymmetric Bragg diffraction: m is the magnification factor, θ_B is the Bragg angle and α is the asymmetry angle. (b) Experimental setup installed at the Materials Science beamline of the Swiss Light Source: visible are both crystals, mounted on their swivels, fixed to the high-resolution goniometers. The beam comes from the right. On the left side, the entrance of the 1:1 optic is also visible.

THEORETICAL BACKGROUND

For σ -polarized X-rays generated by insertion devices of third generation synchrotron facilities, the width of the diffraction pattern for a non-absorbing perfect crystal is given by $\omega_S = \frac{2}{\sin(2\theta_B)} \frac{r_0 \lambda^2}{\pi V} |F_h| e^{-DW}$ where $r_0 = 2.818 \cdot 10^{-15}$ m is the classical electron radius, λ is the wavelength of the incident radiation, V is the volume of the unit cell, θ_B is the Bragg angle, F_h is the crystal structure factor and e^{-DW} is the Debye-Waller factor. Defining the magnification factor as $m = \frac{\sin(\theta_B + \alpha)}{\sin(\theta_B - \alpha)}$ where α is the asymmetry angle, i.e. the angle between the crystal surface and its lattice planes, simple geometrical arguments lead to $S_d = |m| \cdot S_i$, where S_i and S_d are the spatial cross-sections of the incident and diffracted beam. Following Liouville's theorem, it can be deduced that $\omega_i = \sqrt{|m|} \cdot \omega_S$ where ω_i and ω_d are the angular divergences of the incident and diffracted beam respectively. Quantitatively, dynamical theory states that $\omega_i = \sqrt{|m|} \cdot \omega_S$ and $\omega_d = \frac{1}{|m|} \cdot \omega_i$. It follows that if $|m| > 1$ the range of total reflection for the emergent beam is $1/|m|$ times smaller than that of the incident beam, while its spatial cross section is $|m|$ times greater. If two subsequent asymmetrical diffractions with respect to two equal but perpendicular to each other lattice planes occur, we obtain a 2D enlargement of the incoming beam (2D "Fankuchen" effect).

OPERATION WITH THE BRAGG MAGNIFIER

In this paper we summarize the main aspects of the Bragg Magnifier, discussing in particular the properties of the imaging optics and the issues related to the coherence preservation. An extended and more comprehensive theoretical discussion is presented in [12] and lies beyond the aim of this article.

Crystal Preparation

Si(220) crystals with an asymmetry angle of $\alpha = 8^\circ$ have been used as magnifying optics. The crystals have been cut with an angular accuracy of better than 1 arcminute and have been fixed by optical contacting to a precision glass support, the thermal expansion coefficient of which is similar to silicon. The glass support acts as mechanical interface between the silicon crystal and a steel support, which is in turn fixed to a double swivel, ensuring that no mechanical stress is applied to the crystal when the unit is screwed to an high-resolution goniometer, see Fig. 1b. Swivel's pitch and roll accuracy of better than $2''$ as well as goniometer's angular resolution of $0.05''$ perfectly cope with the narrow rocking curves of Si(220), numerically obtained with the help of dynamical X-ray diffraction calculations. Additional details concerning construction and simulations can be found in Ref. [12, 13].

Coherence Preservation and Imaging

The magnified X-ray image, see inset in Fig. 1a, is converted to visible light by a $35 \times 35 \text{ mm}^2$ CsI(Tl) scintillator of 300 micron thickness. The generated light is collected by a high-efficiency 1:1 tandem optic ($f = 150 \text{ mm}$, aperture 1/25, brand "Kinoptik") and projected onto an high-performance CCD camera (THOMSON chip, 2048×2048 pixels, $14 \times 14 \text{ } \mu\text{m}^2$ pitch, 14 bit dynamic range, 250 ms full frame readout).

FIGURE 2. X-ray projection (a) and corresponding line profile (b) of a boron fiber with an outer diameter of $100 \text{ } \mu\text{m}$ and an inner tungsten core of $14 \text{ } \mu\text{m}$. Edge-enhanced radiographic projection (c) and corresponding 3D rendering (d) of a human bone trabecula.

In a previous experiment [13] a gold mesh with nominal aperture of $11 \text{ } \mu\text{m}$ and wire diameter of $5 \text{ } \mu\text{m}$ was imaged while tuning the energy from 21.1 keV up to 22.6 keV, producing magnification factors of 20×20 up to 80×80 , corresponding to pixel sizes of $700 \times 700 \text{ nm}^2$ down to $175 \times 175 \text{ nm}^2$. Fresnel's diffraction effects were clearly observed, but no quantitative consideration could be grasped from that data. In a more refined experiment [14], it has been shown that the Bragg magnifier optics can form magnified in-line near-field holograms at sub-micrometer resolution, with high magnification and high efficiency, confirming therefore the theoretical predictions of Spal [15]. For this purpose, a boron fiber of $100 \text{ } \mu\text{m}$ outer diameter and an inner tungsten core of $14 \text{ } \mu\text{m}$ has been imaged at an energy of 22.64 keV, corresponding to a magnification factor of 60×60 and a pixel size of $235 \times 235 \text{ nm}^2$, see Fig. 2a. On a line profile, see Fig. 2b, at least 4 fringes are visible meaning that the optics preserve the phase information carried by the beam,

i. e. can produce phase contrast images of good quality.

Edge-enhancement usually deteriorates the final resolution of a detector but sometime can be exploited in order to detect tiny, low absorbing inclusions in hard materials. As an example we show here a high-resolution, edge-enhanced radiographic projection of a human bone trabecula, see Fig. 2c. Clearly visible are the few microns sized bone lacunae (osteocytes) within the bone matrix. Performing tomography on the same sample it is possible to obtain the 3D distribution of the lacunae, see Fig. 2d.

DISCUSSION AND OUTLOOK

The first prototype of the Bragg magnifier has been successfully operated and produced high-resolution, aberration free X-ray microradiographs. Reliability, reproducibility and stability of the X-ray optics have been showed to be excellent [12] and high-resolution tomograms have been recorded. It appears clear however that the optics produce strong edge-enhanced images affecting therefore the final spatial resolution. The effect is well pronounced due to the relatively large distance between the sample and the scintillator mounted on the 1:1 optic (350 mm). This large distance is itself determined by the size of the crystals. For this prototype, 160 mm long crystals have been used, in order to magnify $1 \times 1 \text{ mm}^2$ at least 40×40 . Upcoming experiments will try to fully determine the Optical Transfer Function of the system, i.e. to quantitatively characterize the imaging characteristic of the device. Future developments could consider the design of ad-hoc crystals pairs for a given energy or field-of-view.

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