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Transmission-type X-ray linear polarizer with perfect crystals

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Even though conventional X-ray polarizers with multiple-reflection channel-cut structures perform well, they suffer from the disadvantage that the polarized beam is non-stationary as the energy is scanned. In this paper the possibility of using a thin Bragg reflector as a polarizing filter is investigated, so that the transmitted beam (rather than the Bragg-reflected beam) is used. Consequently, the position and direction of the transmitted beam are unchanged as the energy is changed, or even when the polarization direction to be filtered out is changed. Theoretical considerations as well as experimental results on the performance characteristics of the proposed transmission-type X-ray linear polarizer are presented. A polarization ratio, defined as I_H/I_V, higher than 10^5 was obtained.

Keywords: X-ray polarizers; perfect crystals; X-ray polarimeters; dynamical theory of diffraction.

1. Introduction

It is well known that the Thomson scattering amplitude strongly depends on the X-ray polarization state, *viz.* single scattering at 90° produces a linearly polarized X-ray beam (Barkla, 1906; Compton & Allison, 1935). The Bragg reflection at $\theta_B = 45°$ and/or the anomalous transmission through a perfect crystal have been used to obtain a polarized X-ray beam (Cole *et al.*, 1961). Although the former has a higher efficiency than the latter, the polarization ratio decreases quite rapidly with this reflection-type polarizer as the Bragg angle departs from 45°. In particular, a polarization ratio higher than 10^3 can be achieved only in a small range, $45 \pm 0.6°$, of the Bragg angle, this resulting in a limited tunable energy range (Hart, 1978). This problem was overcome by the invention of an energy-tunable X-ray linear polarizer which utilizes multiple reflections in an offset channel-cut device (Hart & Rodrigues, 1979). This device, together with the use of synchrotron radiation, allowed further investigations on X-ray polarization phenomena, *e.g.* resonant X-ray optical activity and Faraday rotation of the plane of polarization (Hart & Rodrigues, 1981; Siddons *et al.*, 1990; Hart *et al.*, 1991; Okitsu *et al.*, 1996).

Achieving an extremely high polarization extinction ratio, typically higher than 10^5, is important since it enables the detection of a very small rotation of the plane of polarization, *e.g.* of the order of 10^{-3} or 10^{-4} rad. For spectroscopic measurements, it is necessary, in addition, to scan the energy of the beam over some range. For some experiments it is also desirable to change the polarization direction. These requirements conflict with the use of the conventional multiple-reflection channel-cut structure, especially for small samples. This is because the position of the reflected polarized beam moves depending on the energy of the beam and/or the polarization direction.

In this paper we propose the possibility of filtering out one polarization state using a thin Bragg reflector. Thus, the transmitted beam is the useful output, which stays exactly at the same position and in the same direction when the energy as well as the polarization direction of the beam are changed. Theoretical considerations on the performance characteristics of the transmission-type polarizer are presented based on the dynamical theory of diffraction. Preliminary data from the transmissivity measurements of diamond and silicon polarizers are compared with theoretical predictions. In addition, experimental results reveal the performance of the proposed polarizer.

2. Theoretical background

Conventional X-ray polarizers work by selecting a beam of one polarization state by Bragg reflection. In contrast, the transmission-type polarizer removes the unwanted polarization state by Bragg reflection and allows the desired beam to pass through undeviated. Practical achievement of this kind of polarizer demands higher perfection of the crystal, since an imperfection of the polarization reflector would result in a low performance instead of a low efficiency. The underlying theory is the dynamical theory of diffraction, which is available for perfect crystals (Zachariasen, 1945; Batterman & Cole, 1964).

The Thomson scattering amplitude depends on the polarization factor, P, which equals unity and $\cos 2\theta$ for the σ- and the π-polarization states, respectively. The dynamical theory of diffraction predicts a region of total reflection for the Bragg reflection by a perfect crystal. In this case, the different polarization states result in different widths of the total reflection region. Thus, when the crystal is set on the Bragg condition, a σ-polarized beam is totally reflected and a transmitted beam is π-polarized. In exact calculations, the transmissivity for the σ-polarized beam is typically less than 10^{-6} over the angular divergence range of about 2 arcsec for the (422) reflection by a 50 µm-thick silicon plate at 7.708 keV photon energy. A diamond perfect crystal is another candidate for the transmission-type polarizer owing to its lower attenuation of the π-polarized beam, enabling us to use a thicker plate with a reasonable attenuation. Calculations show much lower transmissivity of the σ-polarized beam by the diamond than by the silicon. More detailed arguments of theoretical predictions will be given elsewhere.

With the transmission-type X-ray linear polarizer proposed above, the beam is polarized in a limited angular divergence region which satisfies the Bragg condition. The use of an undulator source has an advantage with this kind of polarizer due to the small angular divergence of the beam. For the use of a bending-magnet beamline, the acceptance angle by the perfect crystal should be enlarged in some way. One of the easiest ways is the use of an asymmetric reflection by a perfect crystal. Another is the use of successive multiple crystals with certain offset angles with respect to one another.

3. Transmissivity measurement of perfect crystals

As a preliminary, we measured the transmissivity of the σ-polarized beam with synthetic diamond and silicon perfect crystals on the Bragg condition. The experiments were carried out at a bending-magnet beamline, X12A at NSLS, Brookhaven National Laboratory. As a monochromator and an analyser, four-bounce Si(422) channel-cut crystals were used. Three diamond crystals or a silicon crystal were set in-between. The energy of the incident beam was tuned at the cobalt K-absorption edge, E = 7.708 keV, and the cross section of the beam was reduced to 0.8 (V) × 2.0 (H) mm.

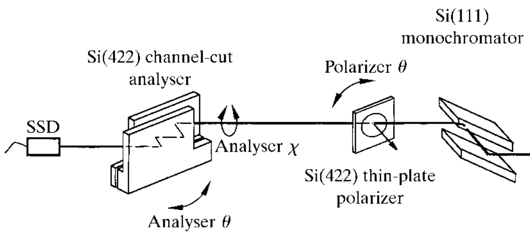

Figure 1
Schematic view of the experimental set-up. The X-ray polarizer was set between the monochromator and the analyser. The analyser can be rotated around the primary beam direction to determine the degree of polarization.

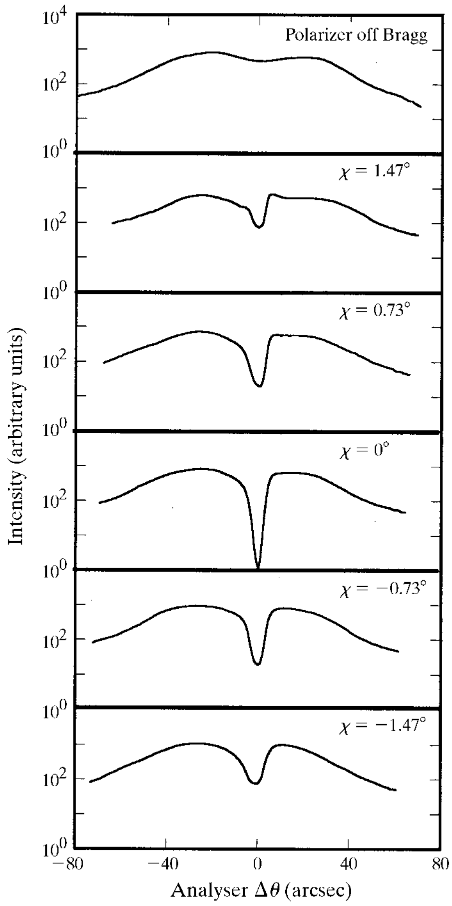

Figure 2
Typical analyser $\Delta\theta$ scan with several rotation angles, χ, of the analyser. Dips are seen due to the removal of the beam of one polarization state, thus showing that the transmitted beam is polarized.

Diamond perfect crystals were 0.3 mm in thickness and were oriented with the (100) direction perpendicular to the plate surface. In order to increase the acceptance angle, we decided to place three crystals successively in the primary beam with slight offset angles with respect to one another. They are aligned to give (311) asymmetric reflections, which additionally increase the acceptance angle, with asymmetric factor b = 0.396 in our set-up. The measured transmissivity of the σ-polarized beam was 5×10^{-3} with the three crystals on the Bragg condition, whereas the theory predicts a value of much less than 10^{-8}. This deviation from the theoretical prediction was considered to be mainly due to the imperfection of the diamond crystals, since the remaining beam intensity in the primary beam direction was found with the analyser scan to be much higher than predicted.

Next, a silicon plate 15 μm in thickness, oriented in the (100) direction, was aligned to give the (422) asymmetric reflection with asymmetric factor b = 0.197. The measured transmissivity of the σ-polarized beam was 1.6×10^{-5} when the silicon plate was adjusted to satisfy the Bragg condition. This extinction value is comparable with the theoretical prediction and we decided to use this silicon plate for performance evaluations of the transmission-type X-ray linear polarizer.

4. Performance of transmission-type X-ray linear polarizer

The experiments were carried out at the bending-magnet beamline X12A at NSLS, Brookhaven National Laboratory. A schematic view of the experimental set-up is shown in Fig. 1. An Si(111) channel-cut monochromator was placed upstream of the silicon thin-plate polarizer. The energy of the incident beam was first tuned at the cobalt K-absorption edge, E = 7.708 keV, and the beam size was set to 0.5 (V) × 1.0 (H) mm. An ion chamber (omitted in the drawing) was inserted after the monochromator to monitor the primary beam intensity. The silicon-plate polarizer was the crystal used in the preliminary experiment and the same (422) asymmetric reflection was used. As an analyser, we used a conventional Si(422) channel-cut crystal with four-bounce reflections and this analyser was placed after the polarizer. The performance of the analyser was established earlier. The analyser was set near the crossed position with respect to the polarizer and was rotated around the primary beam direction, *i.e.* χ scan, so as to investigate the performance of the transmission-type polarizer. A solid-state detector was set down-stream of the analyser.

In our experimental set-up, the polarizer produced a horizontally polarized beam and the analyser selected the remaining vertically polarized component of the beam. In order to characterize the performance of the transmission-type X-ray linear polarizer, the polarization state of the outgoing beam from the polarizer was determined by the analyser χ scan. The production of a polarized beam with the polarizer on the Bragg condition should result in a decrease of the throughput beam intensity. We set the polarizer on the Bragg condition and the analyser was rotated around the normal axis to the beam to satisfy the Bragg condition, *i.e.* $\Delta\theta$ scan. In Fig. 2, $\Delta\theta$ scans of the analyser are shown at several rotation angles, χ. Here, dips are due to the removal of the σ-polarized beam and the deepest dip was accomplished when the polarizer and the analyser were set at the crossed position. Here, a qualitative performance of the polarizer can be seen.

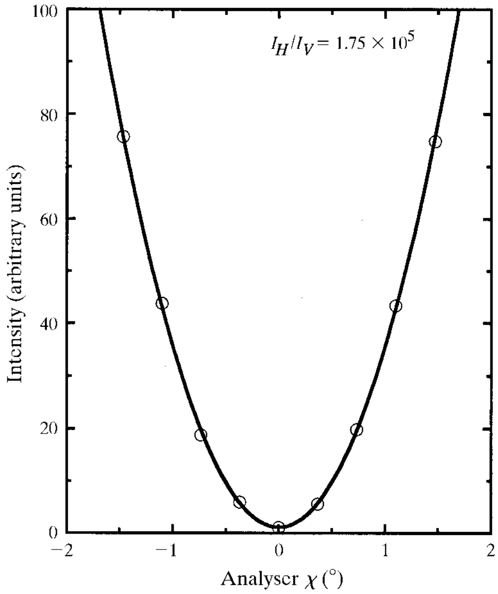

Figure 3
The minimum throughput intensity in the analyser $\Delta\theta$ scan is plotted with the least-squares fits as a function of the rotation angle, χ, of the analyser. The polarization ratio, defined as I_H/I_V, is calculated to be 1.75×10^5.

The minimum throughput intensities of the analyser $\Delta\theta$ scan are expected to modulate sinusoidally as a function of the rotation angle, χ. In particular, parabolic behaviour is seen when the analyser is rotated near the crossed position to the polarizer by a small amount. In Fig. 3, the minimum throughput intensities in $\Delta\theta$ scans are plotted with the least-squares fits of a sinusoidal curve as a function of χ. From the fitting parameters to this analyser χ scan, the polarization ratio, defined as I_H/I_V, is calculated to be 1.75×10^5. This extinction ratio implies that our transmission-type polarizer works quantitatively well.

Finally, the energy of the incident beam was varied around the cobalt *K*-absorption edge. The analyser χ scans with the least-squares fits at several energies of the incident beam are shown in Fig. 4 together with the measured values of the polarization ratio. In all cases, the polarization ratio was higher than 10^5, a level of performance which is adequate for spectroscopic measurements in an X-ray polarimeter.

5. Concluding remarks

We have proposed a transmission-type X-ray linear polarizer using perfect crystals, *e.g.* silicon or diamond. The diamond crystals obtained so far gave poor results due to their imperfection which resulted in a higher transmissivity of the σ-polarized beam than was to be expected theoretically. We have fabricated a transmission-type polarizer with a silicon thin plate and demonstrated its performance characteristics. A polarization ratio higher than 10^5 was accomplished over the energy range ΔE from −7 eV to 3.5 eV near the cobalt *K*-absorption edge. This transmission-type polarizer offers the advantages that the position and the direction of the useful output beam are stationary when the energy is changed or even when the polarization direction to be filtered out is changed. Such characteristics are desirable for spectroscopic measurements in X-ray polarimetry.

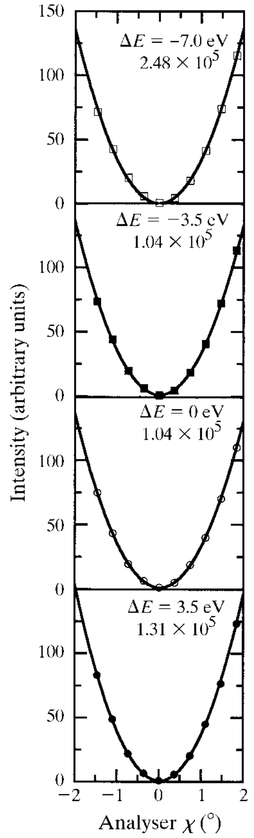

Figure 4
The analyser χ scans with the least-squares fits at several energies of the incident beam together with calculated values of the polarization ratio. In all cases a polarization ratio in excess of 10^5 was obtained.

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