Investigation of X-ray Waveguide Modes on Curved Surfaces

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X-ray reflection from curved surfaces has found many applications for focusing and collimation of synchrotron radiation. The x-ray optical properties of such devices are usually evaluated in terms of geometrical optics. This treatment, however, is not valid anymore for very small radii of curvature. Then the formation of standing waves above the reflecting surface governs the optical properties and a wave-optical calculation has to be performed. This has been demonstrated recently for hard x-rays that were coupled into 'whispering-gallery' waveguide modes on bent Si wafers [1, 2]. Typical radii of curvature were in the range of a few cm. Guided modes on curved surfaces form in a similar way as in planar x-ray optical waveguides [3, 4, 5]. This is illustrated in fig. 1.

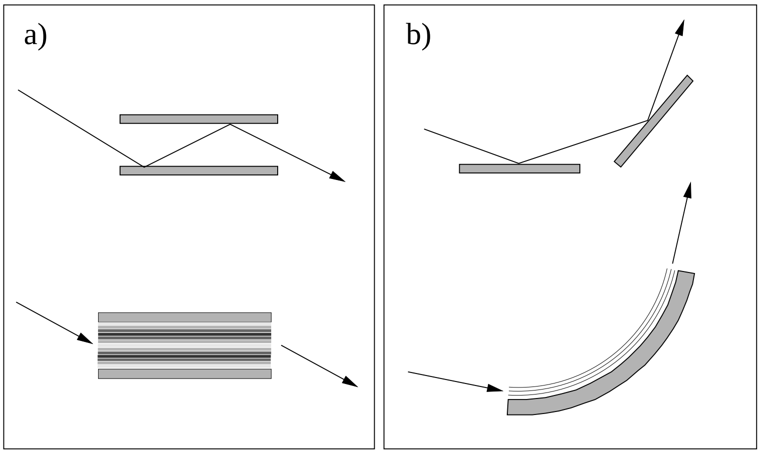

Figure 1: Formation of standing waves a) in planar waveguides consisting of thin films, and b) on curved surfaces

While in a planar waveguide the standing wave forms in successive (+ , –) reflections, guided modes on curved surfaces arise in a sequence of (+ , +) reflections. Planar waveguides are typically realized in thin-film structures where the guided modes suffer substantial absorption in the thin-film material. In contrast, guided modes along bent surfaces can travel over distances of several cm without severe absorption losses.
Similar to a planar waveguide, the modes of a curved waveguide are excited at discrete angles of incidence. Some elementary considerations show that these angles are given by :

$$\varphi_n \approx \left(\frac{n\,\lambda}{2R}\right)^{\frac{1}{3}} \tag{1}$$

where n is the order of the mode, λ the wavelength of the radiation and R the radius of curvature. An important requirement for the existence of these modes is that the φ_n are significantly below the critical angle φ_c. Otherwise the penetration depth of the evanescent wave becomes too large, leading to severe absorption losses already over short distances. The radiation that travels along the waveguide is confined to a region above the surface with a thickness of

$$d \approx 2\,\varphi_n^2\,R \tag{2}$$

The subject of this investigation was the angular dependence of the guided mode in a single-mode waveguide. The experiment was carried out at the beamline BW4. The incident 14.4 keV radiation ($\lambda = 0.86$ Å) was monochromatized to a bandwidth of ~ 3 eV by two subsequent Si(111) reflections. A 60 μm thick superpolished Si wafer was bent to a radius of 30 mm. Its length of arc was 5 mm, thus leading to a deflection angle of 9.5°. According to eq. (1) the angles of the first two guided modes are expected to be φ_1 = 1.13 mrad and φ_2 = 1.42 mrad. These modes should be observable since their angles are significantly smaller than the critical angle of Si which is φ_c = 2.1 mrad at 14.4 keV. The intensity of the x-rays transmitted along the surface of this wafer are shown in fig 2 as a function of incident angle.

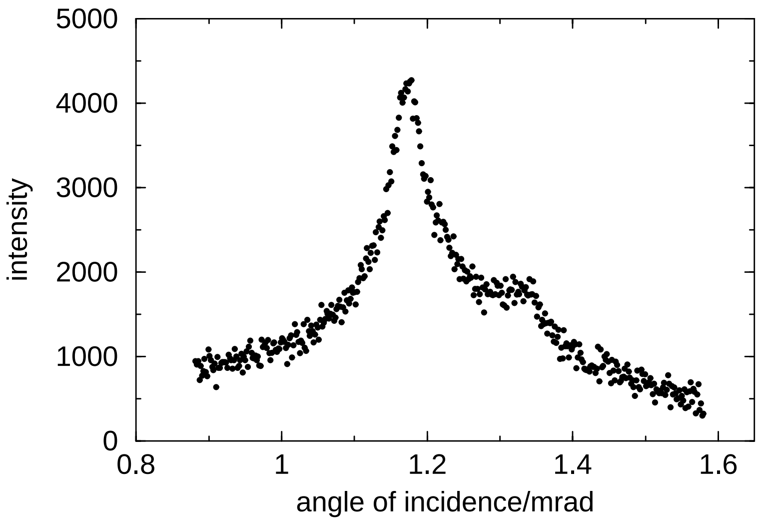

Figure 2: Angular dependence of the intensity transmitted by a Si waveguide with a radius of curvature of 30 mm. The x-rays traveled over a distance of 5 mm along the wafer, confined to an approximately 70 nm thick region above the surface.

The main peak corresponds to the first-order guided mode, the weak satellite peak is most probably due to the second-order guided mode.

Applications of such waveguide may be found in nuclear resonant filtering of synchrotron radiation : Since the critical angle in the vicinity of a nuclear resonance is much larger than the electronic critical angle, such waveguides should transmit preferably resonantly scattered radiation if the surface is coated with the resonant isotope.

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