Synchrotron optics

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Synchrotron radiation is a powerful tool for modern science. To use it most effectively, scientists had to learn how to manipulate with synchrotron radiation. They were forced to develop methods and optical devices which would re-direct, stop or focus synchrotron radiation. Within the next paragraphs I will talk about various optical devices used for synchrotron radiation.
Synchrotron radiation has some unique features, like high flux, brilliance, coherence and polarization. Those properties have to be preserved and respected by synchrotron optics. This requires an enormous demand on the quality of each optical component. There are three basic working principles of synchrotron optics: reflective optics, refractive optics and diffraction optics.
Diffraction based optics are for example monochromator, Fresnel zone plate (FZP) and multilayer optics (ML).
A monochromator, fig.1, selects from an incident spectrum of radiation a certain narrow band of wavelengths $\Delta\lambda$. This selection is based on the Bragg law:

$$2d \sin\Theta_B = n\lambda, \tag{1}$$

where d is the crystallographic plane spacing, Θ_B is the Bragg angle and λ is the wavelength. The most used materials for monochromators are Si, Ge, ML and diamonds.

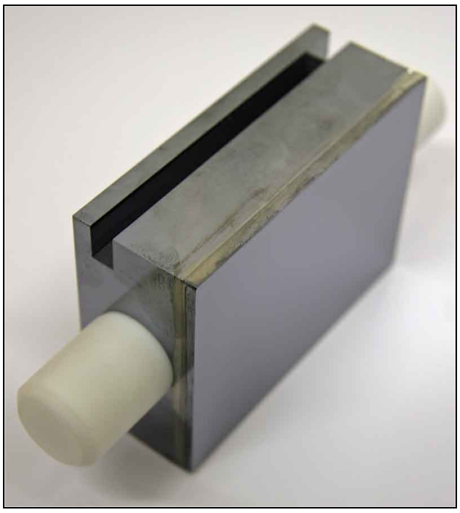

Figure1. An internally water cooled Si monochromator

The material is chosen with respect to the needed properties of the monochromator. For example a ML monochromator has a higher flux than a Si monochromator, but a lower resolution. The shape of a monochromator can be either flat or curved and it can be either cooled or un-cooled. The type of cooling depends on the incident radiation density, which is connected with the radiation source. If we have a beamline with an insertion device, the radiation density is rather large and the monochromator has to be cooled. Cooling can be direct or indirect and the cooling medium can be water or we can use cryogenic cooling.

The second diffraction based optical devices are Fresnel zone plates (FZPs). A Fresnel plate is a circular diffraction grating based on the Fresnel diffraction, fig.2. We can divide them into amplitude ZPs and phase ZPs, their difference is in the diffraction efficiency. A 40% diffraction efficiency is reached by the phase ZPs and only a 10% efficiency is reached in the case of the amplitude ZPs. Their focusing properties have already been discussed in the 19th century, but just in 1952 Baez constructed one for the X-ray region. In the case of the amplitude zones, the focusing results from different absorption between two neighboring zones. On the other hand phase zone focusing results from phase change upon transmission through a zone.

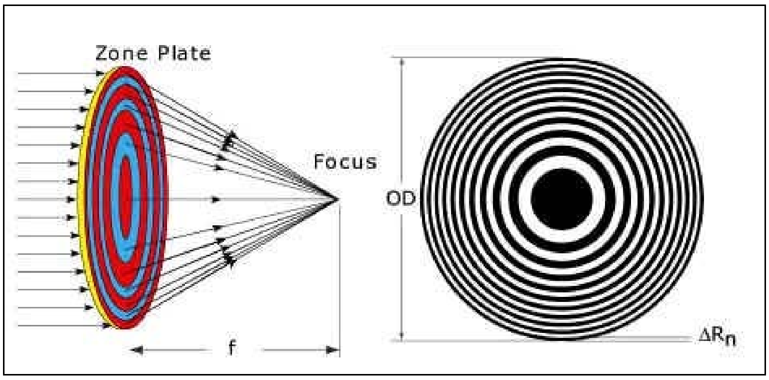

Figure 2. FZP

Multilayer optics (ML) is also diffraction based (fig.3). ML are created by putting two different materials periodically on each other. Mostly there are used several tens or hundreds of layers, with a Λ of 2 – 10 nm. The general rule to optimize ML performance is to choose one material with a high δ and a low β and the other material with a low δ and a high β. Because of the refraction at the surface vacuum-ML the Bragg equation has to be corrected:

$$n \lambda = 2 \Lambda \sqrt{(n^2 - \cos^2\Theta)}, \tag{2}$$

where λ is the wavelength, Λ is A-B layer height and Θ is the incident angle. The advantages of MLs are: high reflectivity – flux, coherent preservation and the adaptability to curved surfaces. Their disadvantages are: complex theoretical description, need of perfect substrate, considerable cost and non – trivial alignment.

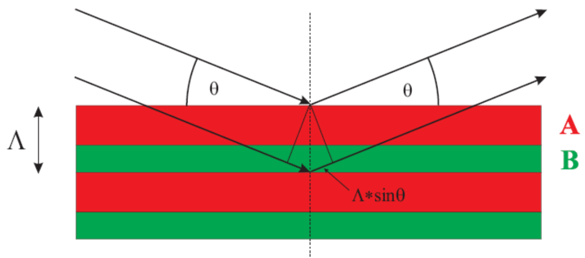

Figure 3. ML structure.

The second working principle is refraction. Compound refractive lenses (CRL) are based on refraction. Refractive lenses made of glass are widely used in the visible region, in 1996 Snigirev *et al.* introduced CRL for the X-ray region. Because of their weak refraction and strong absorption, they can be used only for synchrotron radiation. For their production, low Z materials are used like Li, Be, B, C and Al. Their profile is parabolic, fig.4, and they can be used in energies under 1 MeV.

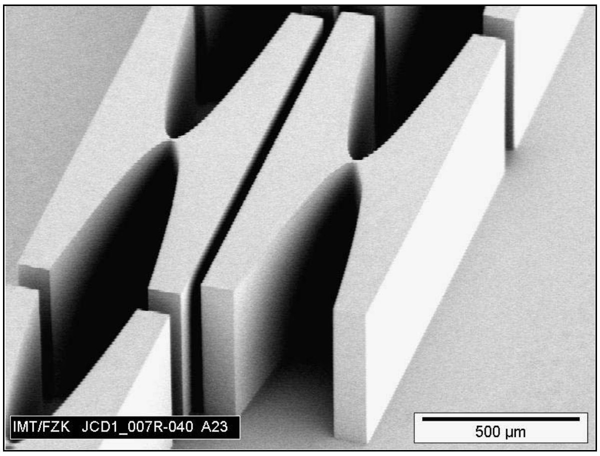

Figure 4. CRL made at FZK

The last group is reflection based optical devices, widely used and well known from the visible region. X-ray mirrors work at the principle of total reflection, which occurs under the critical angle. For hard X-rays the critical angle is very small, 0.1 – 10 mrad., therefore the used material should have a high electron density, like Au and Pl. X-ray mirrors can be used as focusing elements and for removing short wavelengths. The mostly spread configuration is the Kirkpatrick – Baez system (KB), fig.5.

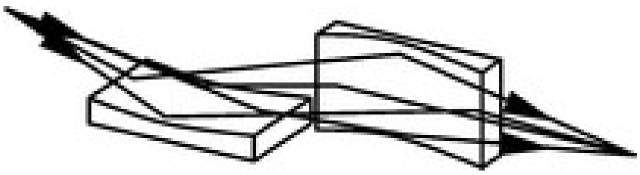

Figure 5. KB system

The next reflection based devices are capillaries. They rely on total external reflection from their internal surface of the tube, this way they also avoid absorption. Their advantages is to create a very small focal point, because the beam size is defined by the exit hole diameter.

The last reflection based device is a waveguide. Its a thin film resonator in which a low absorbing material is enclosed between two metal layers with a small refractive index.