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Review Paper

X-ray optics - a tool for X-ray diagnostic and therapy

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X-ray optics is a relatively new instrument for the configuration X-ray beams. Presently this method is mainly used for diffraction and material tests. Although there are problems for medical use because of the larger wavelength (lower energy), for some applications it might be suitable.

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1. Introduction

After W. C. Röntgen had discovered the X-rays [1] and Max von Laue and his co-worker had proved that these rays can interfere with crystals (1912) the Braggs, father and son, deduced the now called Bragg law:

$$\sin\Theta = n\cdot\lambda/2d \tag{1}$$

($\Theta =$ Bragg angle, $\lambda =$ wavelength of the X-rays, $b =$ lattice plane distance, $n =$ order of interference).

While it took almost 20 years to develop methods for the interference of X-rays in crystals [2-4], the use of X-rays for medicine started almost immediately after the detection. In the literature of 1898 one can find the X-ray image of the bones of a hand [1].

During the last years a large number of X-ray optical instruments have been developed, which are successfully for X-ray diffraction investigations and other applications of material testing [5-18].

Nevertheless, there are possibilities to use these optical instruments for medical applications as well.

The main difference between the medical use of X-rays and that for diffraction measurements is the hardness of the X-rays. While the wavelength for diffraction are in the range of ~ 1 nm (about 10 kV), the wavelength for medical application is more than 10-100 times smaller (50 kV-200 kV). The reason for such large differences is the different interaction of the rays with the object. For diffraction the distance of the lattice planes or other objects is responsible for the measuring results; in medicine the absorption is the main factor of the application. Furthermore the low energy radiation for diffraction has no chance to penetrate larger parts of the human body.

Nevertheless, there are some possibilities to use X-ray optics in medicine.

2. X-ray optics

If an X-ray of a certain wavelength hits a crystal under a certain angle, the beam is reflected according to the Bragg law (Fig. 1). Originally only crystals have been used for those reflections. In the last years more and more multilayers are in use.

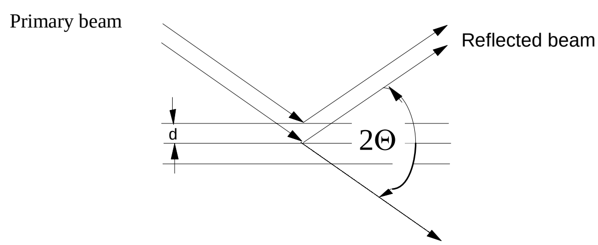

Fig. 1. Simple Bragg reflection.

The simple Bragg reflection might not belong to the X-ray optics, but after bending the crystal the so-called curved monochromator can be seen as the first step to the X-ray optics (Fig. 2).

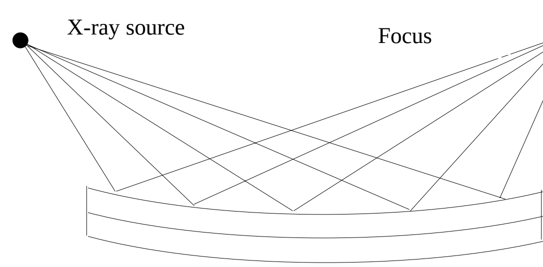

Fig. 2. Curved monochromator.

With this configuration a divergent X-ray beam can be changed into a convergent one. A more exact analysis shows that there must be an additional cylindric polishing to get the Johann-Monochromator (Z. Phys. **69** (1931) 185).

In the last years the name “monochromator“ changed more and more into “mirror“ because for the optics the wavelength plays a minor role.

The next step to an X-ray optics was the invention of the delta crystal [5] and the corresponding multilayer configuration [8].

The main idea was to change the lattice constant inside of the crystal to get the focusing of the beam similar to light optical lens (Fig. 3).

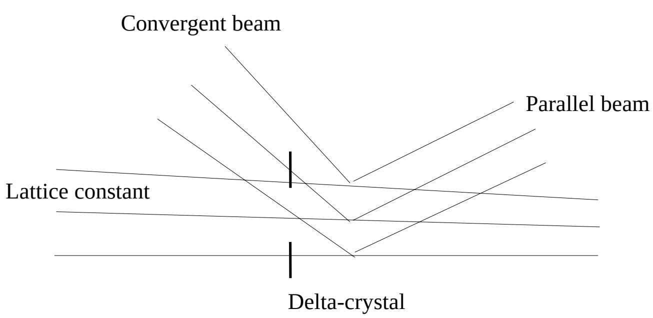

Fig. 3. Crystal with changing lattice constant.

This effect can be used to change a parallel beam into a divergent one or vice versa (Fig. 4). This instrument is a useful tool for the synchrotron radiation as well.

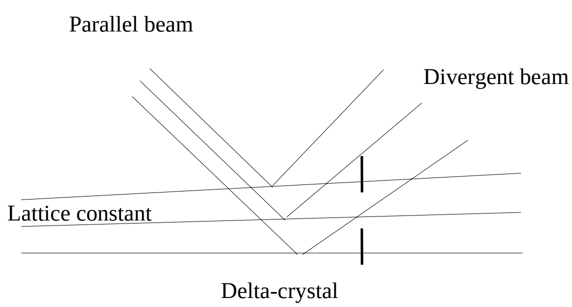

Fig. 4. Crystal with changing lattice constant.

The delta-crystal can be used in two or three dimensions (two vertical delta-crystals) as an X-ray microscope.

Using the delta-crystal, different types of X-ray optics instruments can be designed. One disadvantage though has the delta-crystal: it is very difficult to grow crystals with the required configuration. For an example: A mixture of Silicon and Germanium.

A big progress was the development of multilayers, which can be designed in arbitrary configurations by alternated evaporation of two different materials.

The application of delta-crystals or multilayers to medical purposes has the disadvantage that the optics require relatively low energy X-rays, while in medicine more or less thick samples have to be penetrated.

With the X-ray optics only samples of some cm thickness can be inspected (Fig. 5). Furthermore medical cuttings can be examined.

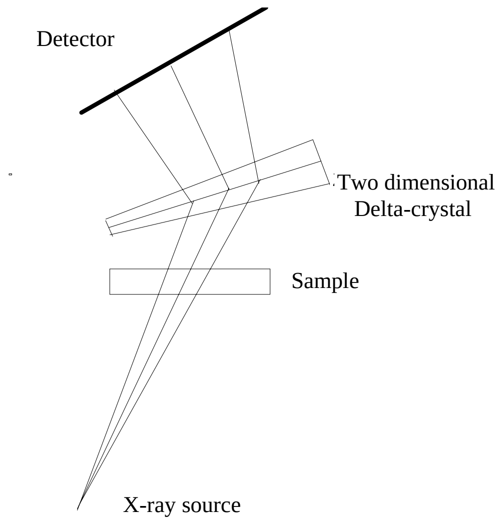

Fig. 5. Scheme of a X-ray microscope.

2.1 X-ray optics using total reflection

A characteristic optical phenomenon, the total reflection, appears for X-rays as well (Fig. 6).

X-ray total reflection has found applications on the basis of grazing incidence in hollow glass capillaries which act as waveguides. The critical angle for total reflection, θ_{cr}, the Fresnel angle, is very low (for glass: θ_{cr}(mrad) ~ 32/E(keV), thus θ_{cr} = 1 mrad = 3 · 4’ for 32 keV radiation). This is a restricyion to longer wavelengths, but at the same time offers the opportunity to partly suppress the shorter wavelengths.

In the simplest form (just one capillary) a small part of an incident divergent beam can be made parallel (down to the value of the Fresnel angle), with some gain in intensity at the place of the sample [15].

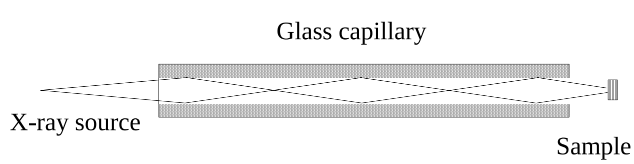

Fig. 6. Glass capillary beam collector.

A multiplication of total reflection can be reached by the use of a bundle of glass capillary. A small change of the X-ray direction can be performed (Fig. 7).

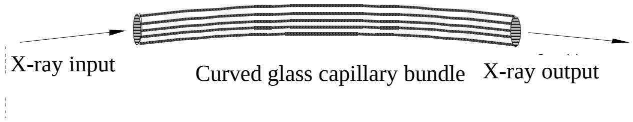

Fig. 7. Glass capillary optics.

It is interesting to remark that these glass bundles can be used to focus the beam. That might be of interest if the aim is to irradiate only small parts of the human body (Fig. 8).

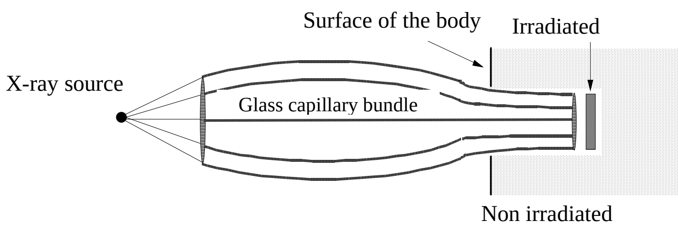

Fig. 8. Directed radiation.

2.2 X-ray reflection

Although the reflection of X-ray is a very interesting field, presently it is not used in medical practice, but mainly for experiments with synchrotron radiation (Fig. 9).

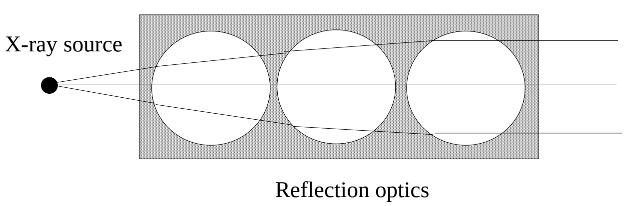

Fig. 9. Reflection at the transfer from material to air (or vacuum).

Further applications of X-ray reflection is a question of using X-ray generators of high power.

2.3 Medical application

Over the last years the application of the X-ray optics became very important, so it is expected that its application for medical purposes will increase in the years to come.

3. X-ray therapy

One of the most serious problems of the X-ray therapy is the fact that not only the sample to be irradiated, but also the surrounding will be effected by the radiation. It depends mainly on the tube voltage, the anode material, the filter, the size of the focus and the slit system.

Using the glass capillary bundle (Figs. 7, 8) the beam can be directed exactly to the selected ill tissue without hiting the surrounding tissues.

Because of the large wavelength (soft irradiation) the absorption (that means the therapy activity) in the surface is very high. So the next layers are hit by only low radiation.

This method is useful for the radiation of internal objects, similar to end anode tubes used in the past (Chaoul tubes).

4. Diagnostic

For the X-ray diagnostic mainly three effects can be used:

a) Parallelization of the beam to get precise optical action.

b) Focusing to a small region by a convergent beam, especially for the use of CCD cameras.

c) Using two optics to design an X-ray microscope; first a convergent beam to the object and then a divergent optic to the detector (Fig. 5).

5. More complicated X-ray optics

More development X-ray optics is envisaged. As an example, multilayer optics can be used on the receiving side of the powder diffractometer (Fig. 10). Moreover, a complex Kirkpatrik-Baez system is of interest for developing a high quality X-ray optics configuration (Fig. 11).

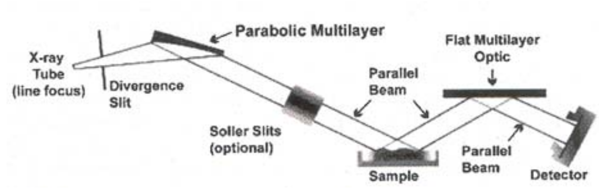

Fig. 10. Multilayer optic used on the receiving side of the powder diffractometer.

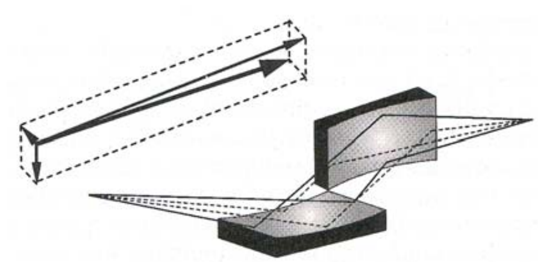

Fig. 11. Kirkpatrick-Baez system.

6. Conclusions

For various reasons including the resolution in VLSI circuits and intensity amplifications, the development of real X-ray optics is necessary. The gradient Delta-crystal seems to be one of the most suitable instruments to approach this goal.

The presented applications of the X-ray optics in medicine are not yet in use.

The possibilities described in this paper evidently can be expanded. The development of the specific instruments is still at the beginning. Here only a hint was given to highlight the direction of the new developments and applications of X-ray optics.

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