Modern X-ray refraction optics in the course of physics of Technical University

E V Smirnov
Bauman Moscow State Technical University, 105005, Moscow, 2nd Baumanskaya, 5
E-mail: seva09@rambler.ru

Abstract. The review of modern achievements in X-ray optics taking into account the refraction of X-rays in the matter is given. The complete external reflection of X-ray radiation from the substance allowing creating mirrors for X-ray radiation is considered. Much attention is paid to the practical use of the whispering gallery effect for X-ray radiation. An analysis of the focusing and collimation of X-ray beams by refractive lenses is given. The urgent need to include this material in the course of physics, as well as in courses on X-ray optics at Technical Universities of Russia, is noted.

1. Introduction

In the extensive spectrum of electromagnetic radiation, the X-ray wavelength range is of great interest to researchers. At the initial stage of X-ray mastering, as is well known, shadow microscopy, photoelectron spectroscopy, as well as X-ray diffraction on crystals were used. Currently, one of the most rapidly progressing directions in modern physical optics is X-ray refractive optics.

In recent decades, X-ray optics, using the concepts and theoretical apparatus of classical optics of visible light, have been increasingly developed. Consideration of the features of the interaction of short-wave radiation with matter leads to X-ray optical analogues that are unusual for traditional optics of visible light and cannot be reduced to simple scaling by the wavelength ratio.

Previously, these sections in the general course of physics at technical universities, as a rule, were not considered. The need to improve the level of training of graduates of Russian Universities, their mastering of this material at the most modern scientific and technical level urgently requires the inclusion of these issues in the general physics course.

It should be noted that a very large range of X-ray radiation interlocks, on the one hand, with a vacuum ultraviolet range at a photon energy of about 100 eV and adjacent, on the other hand, to the gamma-ray region of radioactive nuclei at energies up to 100 keV and higher are becoming more accessible for research. So, for example, very intense X-ray sources based on SR [1], as well as free electron X-ray lasers [2, 3], have now appeared.

When creating focusing devices for X-ray waves, X-ray reflection optics, X-ray diffraction optics, X-ray refractive optics and X-ray waveguides based on thin-film structures are used. This article is devoted, first of all, to X-ray reflection and refraction optics.

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2. X-ray refraction in matter

The refractive index of X-ray radiation is:

\[ n(\omega) = 1 - \beta(\omega) + i\delta(\omega), \]

where the functions \( n, \beta, \) and \( \delta \) are frequency dependent. It should be noted that the refractive index is a complex value, as well as the fact that the numerical values of \( \beta \) and \( \delta \), as a rule, are very small compared to unity and amount to \( \sim 10^{-5} \div 10^{-6} \). The real part of the refractive index \( 1 - \beta \) is responsible for the refraction of radiation, and the imaginary part \( \delta \) is responsible for absorption. A qualitative graph of the dependence of the real part of the refractive index on the frequency \( \omega \) is shown in figure 1.

![Figure 1. Dependence of Re \{n\} on the radiation frequency \( \omega \).](image1)

Usually, the region of anomalous dispersion, in which the transition from the values of \( n > 1 \) to the values of \( n < 1 \), falls into the visible optical range, so that for the following ultraviolet radiation, as well as X-rays and \( \gamma \)-rays, the refractive index \( n \) is less than one. This means that for the specified radiation range, it is not a full internal one that is realized, but a full external reflection of radiation from the surface of the substance. However, due to the smallness of \( \beta \), it occurs at very small slip angles \( \theta \) when the radiation falls on the surface of the substance: \( \theta \leq \theta_c \sim 10^{-5} \). Here, the critical angle \( \theta_c = \sqrt{|1 - \varepsilon|} \), where \( \varepsilon \) is the dielectric constant of the medium, determines the width of the total external reflection region.

The form of the reflection coefficient \( R \), calculated for a sliding incidence of X-radiation as a function of the slip angle \( \theta \), is shown in figure 2 for different absorption values (coefficient \( \delta \)).

![Figure 2. The reflection coefficient at a sliding X-ray incidence for different ratios \( \delta/\beta \): 0 (1) .0.01 (2), 0.1 (3), 0.4 (4), 1.0 (5), 4.0 (6)](image2)

In the absence of absorption \( (\delta = 0) \), the reflection coefficient \( R \) at sliding angles \( \theta \leq \theta_c \) is exactly equal to unity and decreases rapidly when leaving the region of total external reflection \( (\theta > \theta_c) \) (curve 1). In the presence of absorption, \( R \) is less than unity, but if the absorption is small enough \( (\delta \ll \beta) \), \( R \) remains close to unity (curve 2).

The noted features of the total external reflection of X-ray radiation make it possible to rotate the beam of X-rays at any angle practically without losing its intensity, using the “whispering gallery effect” (figure 3).
Figure 3. A diagram illustrating the whispering gallery effect.

Also, this effect allows you to change the direction of the X-ray beam or to focus it with the help of “capillary optics” – the use of one or more tubes-capillaries.

It should be noted that unlike periodic multilayer mirrors, which are spectrally selective, mirrors with whispering modes have a very wide bandwidth. The noted features of the whispering gallery effect make it possible to use it to control synchrotron radiation beams, as well as for the concentration and collimation of X-ray radiation. On the basis of the effect of the whispering gallery of X-rays a method of quality control of concave mirror surfaces of large size can be created.

3. Refractive lenses of X-ray radiation
The next part of the article will focus on refractive lenses of X-ray radiation. It should be noted that an important achievement of modern X-ray optics is the creation of focusing lenses that use the phenomenon of X-ray refraction. The analysis shows that lenses with a parabolic refractive profile (figure 4) have focusing properties. The material for the manufacture of such lenses can serve, in particular, silicon, aluminum, beryllium, various polymers. Note that there is no spherical aberration in paraboloids of rotation.

Figure 4. Focusing on a plane X-ray wave by parabolic refractive profile

Very interesting and promising is the idea of using a system of composite refracting lenses (figure 5). The optical power of such a composite system is proportional to the number of lenses used in the circuit. With a sufficiently large number of consecutively installed lenses, a significant, proportional to the number of lenses occurs, reducing the focal length of the system.
Figure 5. Refractive X-ray lens with double parabolic profile: (a) - a single lens, (b) - a composite set

With the help of such lenses an X-ray analogue of the bilens Billiet optical interference scheme can be realized. Based on it, an X-ray bilens interferometer can be created both in the far and near zones [4].

The idea of manufacturing planar parabolic lenses for X-rays (figure 6) is very interesting and promising. It must be said that focusing of hard X-rays with energy of 100 keV was demonstrated for the first time on composite sets of planar lenses made of silicon. Silicon planar parabolic lenses were also used as refracting collimators with a focal length in the range of several tens of meters.

Figure 6. Planar parabolic lenses: a – snapshot of SEM, b – focal spots for radiation with energy of 17 keV [5]

Experiments were also carried out on focusing X-ray radiation with a matrix of short-focus parabolic lenses (figure 7). The focal lengths of the lenses were 2 cm for CuKα (8.05 KeV) and 6.9 – 9.5 cm for MoKα (17.5 KeV).

Figure 7. Matrix of short-focus parabolic lenses [5]
Figure 8. Image of focal spots of the lens matrix for X-ray energy of 30 keV [5].

Observations were made of interference from two adjacent rows of the matrix, as well as the Talbot effect for images of the matrix of focal spots.

4. Conclusion
Currently, in a number of areas of physics research and technical applications, the phenomenon of X-ray refraction plays an increasingly important role. Therefore, this section should be included in the course of General physics, studied at Technical Universities.

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