The Talbot effect in X-ray range

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Abstract. This article describes the advances made using Talbot effect in X-ray wavelength range. The possibilities of phase-contrast interferometry using a three-grating Talbot interferometer are noted. The achievements of applying the Talbot effect in nanoscale X-ray lithography are discussed. The need to include this material in courses on X-ray optics, read in Russian Technical Universities, is underlined.

1. Introduction
At present, Talbot effect is of considerable interest for specialists working in various fields of physical research – quantum mechanics, wave optics, molecular physics, laser technology, biology, etc. The beauty and visibility of this phenomenon, its deep physical content determined the possibilities of its wide practical application (see, for example, [1-3]), which, undoubtedly, should become the property of the university audience.

In recent years, Talbot interferometry in the X-ray wavelength range has attracted the increasing attention of researchers. In particular, Talbot effect allows one to apply the phase contrast method in radiography and tomography, and, in addition, it can be used in nanoscale X-ray lithography. Let's start with the phase contrast method in radiography and tomography.

2. Three-grating Talbot X-ray interferometer
The studies of Talbot effect in the X-ray wavelength range show that the use of diffraction gratings as optical elements that take into account the phase of X-rays can help to overcome the problems that have so far prevented the use of phase contrast in X-ray and tomography. To obtain X-ray phase contrast images in the field of medical and industrial applications, two- and three-grating Talbot interferometers are used.

Consider a three-grating Talbot interferometer (figure 1). All three grids have the same period and parallel slots. They are located at a distance equal to the length of the Talbot \(L_T\) or several lengths of the Talbot. The meaning of the first lattice is that when using large sources, i.e. in the absence of spatial coherence from the radiation incident on the first grating, the first grating creates a coherent beam falling on the second grating.

One of the advantages of a three-grating interferometer is that it allows you to effectively use standard X-ray sources with sizes larger than a square millimeter. That is, the radiation incident on the first grating \(G_0\) may be spatially incoherent. The first grid \(G_0\) serves as the source grid for creating an array of individually coherent, but mutually incoherent linear sources.

After grating \(G_1\), on which diffraction occurs, the X-ray beam forms periodic interference fringes on the grating plane \(G_2\). The object under study creates phase disturbances in the wave front in the incident beam and leads to displacements of these interference fringes. A grating \(G_2\) with the same
period and orientation of the slits as the interference fringes is placed in front of the detector in order to convert the local position of the fringes into a change in signal intensity. Detecting these movements, you can restore the shape of the wave front and get the image.

Let us consider the results of applying the three-grating Talbot interferometer to a biological object – a small fish, which allows for its differential phase-contrast visualization (Figure 2).

Figure 1. Three-grating Talbot interferometer [3]

Figure 2 shows the results of phase-contrast studies (Figure 2b) in comparison with the usual X-ray image (Figure 2a). Figure 2c, 2d, 2e, 2f, 2g, and 1h are double enlarged images of separate parts of the object for these two cases.

As was to be expected, the skeleton of a fish and its other highly absorbing areas are also visible in varying degrees of detail on an ordinary X-ray diffraction pattern. However, those parts of the object that are either not visible at all or barely distinguishable (Figure 2c, 2e, 2g) are clearly visible in phase-contrast studies (Figure 2d, 2f, 2h).

Figure 2. Differential phase-contrast imaging of biological objects [3]

3. Nanoscale X-ray lithography
As already noted, active research is currently being conducted on the use of the Talbot effect for hard X-rays in lithography processes. We present the results of a study in which a multilayer mask consisting
of several hundred alternating transparent (Si) and opaque (WSi) layers was used instead of a diffraction grating (Figure 3).

![Image of sectional multilayer mask for lithography hard X-rays obtained by SEM](image)

**Figure 3.** Image of sectional multilayer mask for lithography hard X-rays obtained by SEM [4]

These layers were obtained by spraying these substances on a silicon substrate, the period of the multilayer system $d$ was 300nm, and the total thickness of the mask was equal to 10µm. The thickness of these layers in the deposition process was controlled to within a few atomic layers.

Synchrotron x-ray radiation with energy $E=7.5$ KeV and wavelength $\lambda=0.165$ nm was used as a source. The resulting image was recorded on a photoresistor placed behind the mask (Figure 4).

![Schematic diagram of installation for lithography of hard X-rays](image)

**Figure 4.** Schematic diagram of installation for lithography of hard X-rays [4]

According to the Talbot effect, the wave field behind the multilayer mask is repeated at a distance multiple of the Talbot length $L_T = \frac{2d^2}{\lambda}$. For the values of $d$ and $\lambda$ used in the experiment, this distance is a few millimeters, i.e. it is macroscopic, so the installation of the screen (photoresistor) does not cause difficulties.

Figure 5 shows SEM-image of the interference pattern. The results of the experiment show that the wave field in the near wave zone reproduces very well on the Talbot length. Placing the screen at a length of Talbot can provide greater flexibility and maneuverability compared to conventional lithography conditions.
Figure 5. SEM image of a spatial pattern recorded on a photoresistor using hard x-ray radiation (nano-modeling) [4]

Figure 5a presents the SEM image of a spatial pattern recorded on a photoresistor using hard X-rays. The inset shows an enlarged view of the SEM image. Figure 5b shows the contrast of the profile image along a line, perpendicular to the spatial pattern obtained from the SEM image. The intensity averaged over the lines is given at each position on the line.

Although the size of the elements used in work [4] is still large compared with the results of electron-beam lithography, this work is the first step in the application of hard X-ray radiation in the creation of nanoscale images.

5. Conclusion.
Analysis of modern scientific research shows that the Talbot effect in the X-ray wavelength range allows applying the method of phase control in radiography and tomography, and can also be used in nanoscale X-ray lithography. The results of these studies should be included in courses on X-ray optics taught at Technical Universities of Russia.

References
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