The first synthetic X-ray hologram: results

A.A. Firsov\textsuperscript{a,b}, A.A. Svintsov\textsuperscript{b}, S.I. Zaitsev\textsuperscript{b}, A. Erko\textsuperscript{a,*}, V.V. Aristov\textsuperscript{b}

\textsuperscript{a} BESSY, Berliner Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung mbH, Albert-Einstein-Strasse 15, D-12489 Berlin, Germany
\textsuperscript{b} Institute of Microelectronics Technology RAS, Chernogolovka, Moscow distr., Moscow 142432, Russia

Received 22 October 2001; accepted 12 December 2001

Abstract

The first successful reconstruction of a synthetic X-ray hologram is reported. A hologram structure was calculated using a specially developed computer software and fabricated on the surface of a Si(1 1 1) monocrystal using e-beam lithography and a metal coating technique. A “white” broad-band synchrotron radiation beam from the BESSY bending magnet source was used for the hologram reconstruction. The image was obtained at a photon energy of 8 keV and a distance of 0.5 m from the hologram, placed at a distance of 29 m from the source. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: X-ray hologram; Synchrotron radiation

1. Introduction

In 1948 the Nobel Prize Laureate Denis Gabor proposed his famous “method of wave-front reconstruction” which opened the era of holography [1]. In the 1960s with the development of optical lasers, E.N. Leith and J. Upatnieks demonstrated the first wave-front reconstruction by a hologram with a reference beam [2]. Since this first successful hologram demonstration the method of holographic reconstruction has found applications in many different fields of arts, science and technology. The possibility of creating holograms in the X-ray range has also been discussed in a number of works [3]. However, such holograms have neither been fabricated nor tested until now except the case of simple holograms, focusing zone plates. Due to the absence of sensitive and high-resolution materials for X-ray holography, it seems to be more effective to use X-rays only in the reconstruction stage to produce images with micron resolution. A so-called “synthetic hologram” [4] can be generated by computer and transferred into material using modern methods of microelectronics technology [5]. The topic has become even more important with the construction of X-ray lasers in Germany and USA. Here we show the first results of design, optimizing, fabricating and testing of synthetic X-ray holograms.

2. Generation of synthetic X-ray holograms

The principle of X-ray hologram generation is the same as used in hologram generation for
producing images with a laser pointer. The only difference is in the focal position and the relative size of the hologram and image. We have to produce the image at a defined distance from the hologram in comparison with the infinite focal position of the image for a laser pointer.

In the first stage of the generation of synthetic holograms one needs to define the intensity distribution \( I(x, y) \) in the image plane, namely in the reconstructed image

\[
I(x, y) = |R(x, y)|^2, \tag{1}
\]

where \( R(x, y) \) is the complex amplitude of the image. An essential feature of the image demanded is the fact that a phase distribution in the image plane is not important and can be arbitrary.

On the other hand, a hologram may need only to effect a phase modulation \( \varphi(x, y) \) of the incident wave with constant amplitude \( |A(x, y)| \). In this case hologram generation means calculation of such a phase distribution \( \varphi(x, y) \) at \( |A(x, y)| = \text{const} \) such that the interference of X-rays in the focal plane results in the image required.

The phase-shift \( \varphi(x, y) \) is provided by a metallic coating with a thickness modulation. Hard X-rays have a very low absorption in thin layers but the difference in accumulated phase is significant. Moreover, the coating thickness can be optimized to obtain \( \pi \) phase difference for the maximum image contrast.

Let the distance between the image plane and the hologram plane be \( F \) and much larger than the hologram and image size. Then, for the complex amplitude \( R(x, y) \) calculations one can use the low-angle (Fresnel) approximation

\[
R(x, y) = \int \int A(x_1, y_1) \exp\{i\pi[(x-x_1)^2 + (y-y_1)^2]/\lambda F\} \, dx_1 \, dy_1, \tag{2}
\]

where \( A(x, y) = |A(x, y)| \exp[i\varphi(x, y)] \) is the complex amplitude distribution of the wave in the hologram plane and \( \lambda \) is the wavelength of the radiation used.

The complex amplitudes can be redefined as follows:

\[
A_1(x_1, y_1) = A(x_1, y_1) \exp[i\pi(x_1^2 + y_1^2)/\lambda F] \tag{3}
\]

and

\[
R_1(x, y) = R(x, y) \exp[-i\pi(x^2 + y^2)/\lambda F]. \tag{4}
\]

This is effectively a phase lens with a focal length equal to \( F \). The two-dimensional Fourier transform for the complex amplitude of hologram and image is

\[
R_1(x, y) = \int \int A_1(x_1, y_1) \exp[-i2\pi(x_1 \ast x + y \ast y_1)/\lambda F] \, dx_1 \, dy_1. \tag{5}
\]

The computer generation of the hologram consists of iterative calculations of the hologram phase distribution under the condition of constant value of intensity of the complex amplitude \( A(x, y) \) in the hologram plane using direct \( (A_1 \to R_1) \) according to (6a) and (6b) and reverse \( (R_1 \to A_1) \) Fourier transformations to define the image amplitude to be “as close as possible” to the image required. Due to the use of the redefined complex amplitudes \( A_1 \) and \( R_1 \) (see Eqs. (3) and (4)) we can now use the algorithm of fast Fourier transformation iteratively instead of a time-consuming two-dimensional numerical integration for the original complex amplitudes \( A \) and \( R \) in (2).

The word “X-RAY” composed of \( \delta \)-function pixels has been chosen as the object (Fig. 1). For the hologram fabrication we employ the principle employed in the generation of the Bragg–Fresnel optical elements: a combination of the Bragg diffraction on a single-crystal and Fresnel focusing on a surface profile [6]. The synthetic hologram has been designed as a phase-shift mask placed on a polished surface of a Si(111) crystal. An initial hologram structure on the resist was fabricated by electron-beam lithography in the JSM-840 microscope controlled by the “Proxy for Windows” program package. After the development of the resist, a Ni layer was deposited, followed by the lift-off procedure. The thickness of the Ni layer was 340 nm, calculated to produce a \( \pi \) phase-shift at the energy of 8 keV and Bragg incidence angle of 14.2°. Thus, the hologram is a phase-shifting layer of a Ni film on a silicon substrate simultaneously serving both as a Bragg mirror and as a monochromator for the incident radiation (Fig. 2). The design parameters of the hologram are the following: photon energy 8 keV (\( \lambda = 0.155 \) nm),
aperture 270 µm, minimum period of interference fringes 0.6 µm, hologram–image distance 500 mm.

The synthetic hologram is fabricated assuming an ideal coherent source. The only limitation on spatial resolution is the minimum structure period of the e-beam writing process. The resolution of a synthetic hologram reconstruction is similar to the resolution of an X-ray Fresnel zone plate in partially coherent illumination. Each point of the source reconstructs the whole hologram image with a resolution defined by the size of the emitting source area.

3. Experimental results

In our case the source size of a BESSY bending magnet is 40 µm horizontally and 65 µm vertically. The spatial resolution can be estimated using equations

\[ \delta_x = \frac{Fd_s}{L}, \]
\[ \delta_y = \frac{Fd_s}{L}, \]

where \( L \) is the source–hologram distance, \( \delta_x \) and \( \delta_y \) are the spatial resolution in the image plane, \( d_s^x, d_s^y \) are the source size in the horizontal (x) and vertical (y) directions. Taking into account the experimental parameters: \( L = 29 \) m; \( F = 0.5 \) m; and the source size we arrive at a value of \( \delta_x = 0.7 \) µm and \( \delta_y = 1.1 \) µm.

The chromatic (longitudinal) resolution limit is defined by the monocrystalline silicon substrate, which reflects photons within a very narrow energy bandwidth. The energy bandwidth can be estimated by the Bragg equation in differential form

\[ \Delta E/E = \delta \theta \cot \theta_B + \delta \theta, \]

where \( \delta \theta = 1.4 \times 10^{-4} \) is the intrinsic Si(1 1 1) crystal energy resolution at the Bragg angle of \( \theta_B = 14.2^\circ \) and \( \delta \theta \) is the opening angle of in the plane of diffraction. According to (7) the reflected energy spectrum has a width of \( \Delta E/E \sim 1.5 \times 10^{-4} \). Then the chromatic resolution limit due to a chromatic aberration is equal to

\[ \delta_{\text{chrom}} = 0.61[\lambda F(\Delta E/E)]^{0.5} \sim 0.07 \text{ µm}. \]

The depth of focus within the resolution limit of 1.1 µm can be estimated using a zone plate equation

\[ \Delta z = \pm 2(\delta_x)^2/\lambda \sim 15.7 \text{ mm}. \]

Thus, the registration of a holographic image can be done using X-ray sensitive material with a large thickness.
Experimental tests of the hologram reconstruction were done at a BESSY white-beam dipole beamline. There were no optical elements except apertures between the source and the synthetic hologram. The distance between the source and the hologram was 29 m. The reconstructed image was recorded on a high-resolution X-ray film and enlarged using an optical microscope. The result of the reconstruction is shown in Fig. 3. At the distance of 500 mm from the hologram we have obtained an image “X-RAY”. The image resolution was estimated to be of the order of 2.4 μm using microdensitometry of the image edges. The estimated theoretical resolution is still better than the measured value. The loss of resolution could be explained by error in alignment, by film resolution or by inaccuracy of technological steps in reproducing of the smallest details of the hologram.

4. Conclusions

We have reported the first experimental results of a new method of high-resolution imaging in the X-ray energy range, namely synthetic X-ray holography. The transverse and longitudinal resolution limits due to the source size in combination with monochromatic reflection from the single-crystal substrate of the hologram were found to be (theoretically) enough to obtain a resolution of the order of ~1 μm with a focal depth of 15 mm. We expect to reach the theoretical values using X-ray resists instead of photo-emulsion film. Extrapolations for X-ray laser sources give us a possible resolution limit of a few tenths of micrometers. This method should find applications in high-energy lithography (LIGA technology), for the projection printing of micron size structures in a very deep resist layers as well as in micro-objects.
imaging, in material diagnostics (e.g. in X-ray differential phase contrast microscopy) of solid-state and biological samples.

Acknowledgements

The authors are very grateful to colleagues from BESSY and IMT RAS for their help in performing the experiment. We thank Prof. W. Gudat and Prof. W. Peatman for support, discussion and encouragement. The work was partially supported by National (Russia) Program on “Physics of Nanostructures” Grant 97-2021.

References