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X-ray wideband in-line holography using a zone plate

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X-ray wideband in-line holography, a new X-ray holography geometry using a zone plate, is proposed. The temporal coherence requirement in this geometry can be very low.

Keywords: X-ray holography; temporal coherence.

1. Introduction

Currently available methods of soft X-ray holography such as in-line holography and Fourier transform holography (Jacobsen *et al.*, 1990; McNulty *et al.*, 1992) have a resolution of tens of nanometers. A monochromaticity ($\lambda/\Delta\lambda$) of several hundred is required. X-ray wideband in-line holography (Zhu, 1995; Chen *et al.*, 1997), a new geometry of soft X-ray holography in which the requirement for temporal coherence can be very low, is reported here.

2. X-ray wideband in-line holography

Wideband in-line X-ray holography geometry is constructed by inserting a microzone plate into the in-line holography geometry (Gabor, 1948), as shown in Fig. 1. The first diffraction order from the focus of the zone plate serves as the reference wave, and the zeroth order illuminates the specimen downstream from the focus to produce the object wave. In order to illuminate the specimen, the first zone in the centre of the zone plate is transparent. An order-sorting aperture (OSA) in the focal plane is used to select the first order and zeroth order.

A spatially coherent X-ray beam is required to illuminate the zone plate, and according to Fourier analysis

$$A\varphi = AD/Z_a \leq \lambda/2, \tag{1}$$

where A is the diameter of the aperture, D is the diameter of the zone plate, φ is the angle which D subtends at the aperture, Z_a is the distance between the aperture and the zone plate and λ is the effective wavelength. In this geometry

$$Z_a \geq 2AD/\lambda \gg Z_f > Z_o, \tag{2}$$

where Z_o is the distance from the specimen to the hologram and Z_f is the distance from the focal point to the hologram. All aperture-to-zone-plate X-ray paths can be regarded to be approximately Z_a.

For simplicity, only the path difference between the reference and the object point on the axis will be calculated. The reference path L_r from the aperture to a point on the hologram is

$$\begin{aligned} L_r &= Z_a + [(Z_f + f)/Z_f](Z_f^2 + R^2)^{1/2} \\ &= Z_a + (Z_f + f)[1 + (R^2/2Z_f^2) - (R^4/8Z_f^4)], \end{aligned} \tag{3}$$

where R is the radius of the point and f is the focal length. The object path L_o from the aperture to the same point is given by

$$\begin{aligned} L_o &= Z_a + f + (Z_f - Z_o) + (Z_o^2 + R^2)^{1/2} \\ &= Z_a + Z_f + f + (R^2/2z_o^2) - (R^4/8Z_o^4). \end{aligned} \tag{4}$$

The path difference between the reference and the object is given by

$$\begin{aligned} \Delta L &= |L_r - L_o| \\ &= \left| [Z_o(Z_f + f) - Z_f^2]\frac{R^2}{2Z_oZ_f^2} - [Z_o^3(Z_f + f) - Z_f^4]\frac{R^4}{8Z_o^3Z_f^4} \right|. \end{aligned} \tag{5}$$

If

$$Z_o(Z_f + f) = Z_f^2, \tag{6}$$

then

$$\begin{aligned} \Delta L &= (Z_f^2 - Z_o^2)R^4/8Z_o^3Z_f^2 \\ &= (Z_f + Z_o)fR^4/8Z_o^3Z_f^2 \\ &< R^4/4Z_o^3. \end{aligned} \tag{7}$$

Since the path difference ΔL should be smaller than the coherence length, *i.e.*

$$\Delta L \leq \lambda^2/\Delta\lambda, \tag{8}$$

and

$$R_{\max}/Z_o \leq \lambda/\delta, \tag{9}$$

where δ is the transverse resolution, the effective bandwidth is given by

$$\lambda/\Delta\lambda \geq Z_o\lambda^3/4\delta^4. \tag{10}$$

For example, when δ = 60 nm, λ = 3 nm and Z_o = 4 mm (implying Z_f = 5 mm and f = 1.25 mm), substituting these values and (9) into

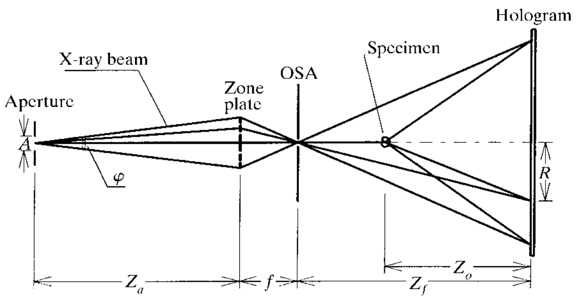

Figure 1
Schematic diagram of X-ray wideband in-line holography.

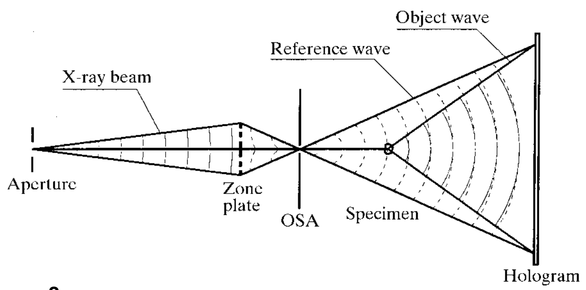

Figure 2
Schematic diagram of the principle of X-ray wideband in-line holography.

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(7) and (10) gives $\Delta L < 6$ nm and $\lambda/\Delta\lambda \geq 2$. According to these values, the coherence requirement of X-ray in-line holography is very low.

The principle behind this kind of holography is figuratively shown in Fig. 2. Although equiphase surfaces of the reference wave from the focus of the zone plate are spherical, rays emerging simultaneously from the aperture do not reach the focus at the same time. This means that the equitime surfaces are not spherical after the zone plate. The equiphase surfaces after the zone plate are constructed from different equiphase surfaces before the zone plate, so the equiphase surfaces and the equitime surfaces necessarily separate from each other. Diverging equiphase spheres are transformed into converging equiphase spheres by the process of diffraction by the zone plate, but diverging equitime spheres are changed into aspherical surfaces. In Fig. 2, the solid lines represent the equitime surfaces which are the same as the equiphase surfaces, and the dashed lines represent the equitime surfaces which are different from the equiphase surfaces. If the condition (6) is satisfied, the path difference between the reference and the object can be very small. The critical point is that path differences between rays from different wave zones of the zone plate can be used to compensate for path differences between the reference and the object.

The results in (7) and (10) can also be obtained in a different but equivalent way, by decomposing the incident X-ray beam into a sum of contributions from different frequency components with a dispersion of focal positions. The OSA only stops non-axial zeroth-order and high-order X-rays, so its internal diameter can be large enough to allow wideband X-rays to pass through. We can easily come to the conclusion that if the condition (6) is satisfied, the different monochromatic interference patterns will remain approximately in step.

Further calculations show that the path difference for an object point off the axis is

$$\Delta L < |(\lambda/\delta)^4(Z_o/4) \pm Rr/Z_o| \simeq |(\lambda/\delta)^4(Z_o/4) \pm \lambda r/\delta| < (\lambda/\delta)^4(Z_o/4) + \lambda r/\delta, \qquad (11)$$

where r is the radius of the object point. If the radius r is 2 μm, then substituting the values of δ, λ and Z_o used previously into (11) gives $\Delta L \leq 0.1$ μm.

The characteristic quasi-equal-path of this kind of holography could be used to obtain information on the two-dimensional spatial coherence of an X-ray beam.

3. Conclusions

A new geometry for X-ray wideband holography is proposed in this paper. The path differences between rays diffracted by the zone plate from different wave zones can be used to compensate for the path differences between the reference and the object, making the requirement for temporal coherence of the X-ray beam very low.

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