Pinhole diffraction holography for fabrication of high-resolution Fresnel Zone Plates

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Abstract: Fresnel zone plates (FZPs) play an essential role in high spatial resolution x-ray imaging and analysis of materials in many fields. These diffractive lenses are commonly made by serial writing techniques such as electron beam or focused ion beam lithography. Here we show that pinhole diffraction holography has potential to generate FZP patterns that are free from aberrations and imperfections that may be present in alternative fabrication techniques. In this presented method, FZPs are fabricated by recording interference pattern of a spherical wave generated by diffraction through a pinhole, illuminated with coherent plane wave at extreme ultraviolet (EUV) wavelength. Fundamental and practical issues involved in formation and recording of the interference pattern are considered. It is found that resolution of the produced FZP is directly related to the diameter of the pinhole used and the pinhole size cannot be made arbitrarily small as the transmission of EUV or x-ray light through small pinholes diminishes due to poor refractive index contrast found between materials in these spectral ranges. We also find that the practical restrictions on exposure time due to the light intensity available from current sources directly imposes a limit on the number of zones that can be printed with this method. Therefore a trade-off between the resolution and the FZP diameter exists. Overall, we find that this method can be used to fabricate aberration free FZPs down to a resolution of about 10 nm.

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References and links

1. J. Kirz, C. Jacobsen, and M. Howells, “Soft x-ray microscopes and their biological applications,” Q. Rev. Biophys. 28(1), 33–130 (1995).
2. W. S. Haddad, I. McNulty, J. E. Trebes, E. H. Anderson, R. A. Levesque, and L. Yang, “Ultahigh-resolution x-ray tomography,” Science 266(5188), 1213–1215 (1994).
3. M. Young, “Zone plates and their aberrations,” J. Opt. Soc. Am. 62(8), 106–110 (1962).
4. G. L. Rogers, “Gabor diffraction microscopy: the hologram as a generalized zone-plate,” Nature 166(4214), 237 (1950).
5. M. H. Horman and H. H. M. Chau, “Zone plate theory based on holography,” Appl. Opt. 6(2), 317–322 (1967).
6. H. H. M. Chau, “Zone plates produced optically,” Appl. Opt. 8(6), 1209–1211 (1969).
7. H. Ming, Y. Wu, J. P. Xie, and T. Nakajima, “Fabrication of holographic microlenses using a deep UV lithographed zone plate,” Appl. Opt. 29(34), 5111–5114 (1990).
8. G. Schmahl, D. Rudolph, P. Guttmann, and O. Christ, “Zone plates for x-ray microscopy,” X Ray Microsc. 43, 63–74 (1984).
9. Y. B. Yun and M. R. Howells, “High-resolution Fresnel zone plates for x-ray applications by spatial-frequency multiplication,” J. Opt. Soc. Am. A 4(1), 34–40 (1987).
10. J. E. Trebes, S. B. Brown, E. M. Campbell, D. L. Matthews, D. G. Nilson, G. F. Stone, and D. A. Whelan, “Demonstration of x-ray holography with an x-ray laser,” Science 238(4826), 517–519 (1987).
11. S. H. Lee, P. Naulleau, K. A. Goldberg, C. H. Cho, S. Jeong, and J. Bokor, “Extreme-ultraviolet lensless Fourier-transform holography,” Appl. Opt. 40(16), 2655–2661 (2001).
12. P. W. Wachulak, R. A. Bartels, M. C. Marconi, C. S. Menoni, J. J. Rocca, Y. Lu, and B. Parkinson, “Sub 400 nm spatial resolution extreme ultraviolet holography with a table top laser,” Opt. Express 14(21), 9636–9642 (2006).
An FZP is diffraction based optical lens commonly used in the x-ray wavelength region due to the difficulty of using conventional lenses and mirrors in this spectral range. Fabrication of high resolution FZPs is critical in the realization of the inherent high spatial resolution potential afforded by the short wavelength of x-rays. X-ray microscopy [1], and high-resolution x-ray tomography [2] are among many applications that require such lenses. Zone plates are made of concentric rings or zones [3] of absorbing or phase shifting materials of zones) of its outermost zone.

A similarity between holograms and Fresnel zone plates has been established by G. L. Rogers [4] in one of the early works in the field of holography. A hologram is considered to be a generalized zone plate which when illuminated with a point source generates the image of the parent object. More detailed work has been presented to establish the fact that a Fresnel zone plate is a special type of hologram [5] which was experimentally demonstrated by recording the fringe pattern created by the interference of a spherical and a plane wave obtained from a He-Ne Laser on a photographic emulsion plate [6]. More recently holographic fabrication of micro-lenses has been demonstrated in deep UV regime [7] by interfering first and second order diffracted waves from an ion etched Fresnel zone plate. Fabrication of FZPs with UV laser sources using aspherical optics has been studied by G. Schmahl and associates [8] and such lenses have been successfully used for imaging at soft x-ray wavelengths. Theoretical understanding on recording zone plates from a relatively low resolution one by interfering light diffracted from positive order foci was also proposed [9].

While holographic fabrication is a well established method in the visible and UV ranges, thanks largely to the availability of highly coherent and powerful laser sources, application to shorter wavelengths has remained more challenging due to difficulties with availability of suitable sources and optics. However, potential for achieving higher spatial resolution coupled with advances in x-ray sources and optics offer promises in this field. Holography using x-ray wavelengths. Theoretical understanding on recording zone plates from a relatively low resolution one by interfering light diffracted from positive order foci was also proposed [9].
lasers [10] and synchrotron radiation sources has already been reported [11]. Recently, a table top EUV source has been used to demonstrate sub-400 nm resolution holography [12]. First demonstration of zone plate fabrication using EUV radiation was performed by recording diverging and converging diffracted spherical waves generated by two concentric annular parent zone plates [13]. Initial results on holographic lithography at EUV wavelength (13.5 nm) was also reported recently [14].

Fig. 1. Schematic of the holographic exposure technique. EUV plane wave incident on the mask (membrane containing pinhole) undergoes diffraction through the pinhole and interferes with transmitted plane wave to form zone plate pattern that is recorded in sensitive resist material coated on a substrate placed at a distance $z$ from the mask. $r$ is the radial coordinate in the image plane.

High resolution ZPs are conventionally fabricated with electron beam lithography (EBL) technique [15, 16]. Even though EBL is one of the most powerful techniques to fabricate nano-patterns, it needs to address certain issues like proximity effect [17] (broadening of the written feature size due to secondary electrons), finite pixel size, pattern placement accuracy and relatively long exposure times. Holographic fabrication in the EUV region has potential to overcome these limitations. Photon based interference lithography (IL) using EUV light offers practically no proximity effect allowing one to write dense periodic pattern [18]. In fact highest resolution linear gratings to be recorded with a photolithographic method (half-period $= 8$ nm) have been fabricated [19] using EUV interference lithography. However, an FZP is different than a linear grating and special holographic methods need to be developed for effective use of the available light sources and optics in the EUV region. In this paper, we explore the use of a pinhole diffraction scheme [20] in conjunction with a synchrotron source for fabrication of high-resolution FZPs. Fundamental and practical aspects of this optical scheme are considered and limitations that stem from properties of materials and light sources used in forming and recording of the holographic pattern are analyzed.

2. Holographic principle

Our holographic approach is based on the idea that a zone plate is a hologram of a point source. A diverging spherical wave from a point source interfering with a plane-wave front generates the hologram of the point source itself. The diverging spherical wavefront is created through diffraction by a nanometer scale circular aperture that is opened in a semi-transparent film (membrane). The pinhole bearing membrane is illuminated with a monochromatic EUV plane wave and the light diffracted by the pinhole interferes with the plane wave that is partially transmitted by the membrane to create interference fringes which are in the form of an FZP. The fringe pattern is recorded in a photoresist film and the resulting pattern is processed to form an FZP. Hence the attenuated plane wave transmitted by the membrane can
be considered as the reference wave that interferes with the diverging spherical wave to produce a hologram of the point source like pinhole (Fig. 1).

In order for this approach to be valid, the beam that is diffracted by the pinhole needs to accurately approximate a spherical wave. The diffraction pattern from such a pinhole can be described by the Airy function [21] which in the far field, is similar in phase to that of a spherical wave emitted by a point source. The pinhole diameter (d), wavelength (λ) and distance between the pinhole and the image plane (z) needed in practice generally justify the use of the far field approximation (z > 2d²/λ). For example, using a pinhole of diameter d = 300 nm, illumination wavelength λ = 13.4 nm and z varying from 100 µm to 400 µm, one can see that the far field approximation is easily satisfied. When this is the case, the interference fringes in the form of a concentric series of circles are produced. The radius (r_n) of the nth maximum or minimum is found to follow the equation r_n^2 = nλf + n²λ²/4 which is the construction equation of a Fresnel zone plate with a focal length of f. The holographic principle implies that the distance between the pinhole and the image plane (z) is equal to the focal length f of the fabricated zone plate.

In theory, a holographic recording contains spatial information related to the object limited only by the wavelength of the used light. However, we also need to consider the response of the material (photoresist in our case) that is used in the recording process, which is typically binary. In other words, depending on the relative value of the exposure dose with respect to the dose threshold of the photoresist, the photoresist is either removed from the surface during the development process or it remains. Therefore, in practice only part of the interference pattern can be recorded that shows significant variation around the photoresist dose threshold. For this reason the two interfering waves, i.e. the spherical and plane waves, need to have comparable intensity in order to create a fringe pattern with sufficient modulation for recording in the photoresist layer. Now, we consider that the diffracted beam is described by the Airy equation and outside its central lobe the Airy pattern has much weaker intensity (the maximum intensity in the 2nd lobe is only 1.75% of the central lobe). This large difference makes simultaneous recording of the interference pattern due to the central and side lobes in a photoresist very difficult. Therefore we mainly restrict ourselves to the principal Airy lobe. This, in turn, puts a limit on the smallest possible outermost zone width (Δr_N) that can be recorded with this scheme. In the following sections we show that this limit is described by the equation Δr_N = d/2.44.

Refractive index (n) of materials at soft x-ray regime is given by n = 1-δ-iβ, where δ and β account for phase shift of the wave front and absorption of the field amplitude when propagating through the material, respectively.

3. Experimental procedure and results

We briefly outline the experimental procedure used in the demonstration of the scheme here for the sake of completeness as a detailed description has been reported earlier [20]. The pinhole is fabricated by electron beam lithography (LION LV-1, Leica, Jena) on a 100 nm thick silicon nitride membrane coated with 23 nm thick chromium film. Poly-(methyl methacrylate) (PMMA) was used as a resist layer. The pinhole pattern is etched through the membrane by reactive ion etching (RIE) using the thin Cr layer as a hard mask. An additional gold (Au) layer is subsequently deposited on the membrane as an absorbing material in order to control the intensity of the plane reference wave. The pinhole aperture remains open during this last step. The membrane containing the pinhole is used for EUV holographic exposures at the X-ray Interference Lithography (XIL) beamline of the Swiss Light Source (SLS). EUV beam is obtained from an undulator source and it has a central wavelength of 13.4 nm and a spectral bandwidth of 2.5%. The intensity of the beam transmitted by the membrane was only about 0.01% of the incident radiation [22], i.e., the plane wave was attenuated by a factor of 10⁶ which is required to make the diffracted and transmitted beam intensities similar at the exposure plane. The resulting pattern is recorded on another Cr (23 nm) coated silicon nitride membrane (100 nm thick) using a sensitive chemically-amplified EUV resist (MET 2D) [23] and transferred to the membrane underneath using RIE.
SEM images of zone plate patterns obtained by the use of three pinholes of different diameters are shown in Fig. 2. Qualitatively, it is observed that the zone plate obtained with the smallest pinhole is the largest in diameter. The diameters of the zone plates are not inversely proportional to the pinhole diameters as one would expect from a simple pinhole diffraction theory, as the pinhole diameter has a strong influence on the precise modulation of the fringe pattern to be printed, as discussed in detail in the following section.

The distance between the mask and the substrate is chosen (discussed later) in consideration of the absorption of the membrane and the diameter of the diffracting pinhole. As a membrane typically contained more than one pinhole, usually of different diameters, the gap between the mask and the substrate, as well as the exposure dose, were varied in order to achieve the best exposure parameters for recording FZP patterns. The effect of varying the dose while keeping the pinhole diameter and the exposure distance fixed is shown in Fig. 3. The number of zones and the diameter of the zone plate depend on the exposure dose. When the exposure dose is low only the central zones are printed which always have the highest intensity due to the intensity distribution in the Airy pattern. A large number of zones is printed at the optimum dose (panel c). Increasing the dose further results in over-exposure and complete removal of the (positive tone) photoresist in the outer zones due to the low fringe modulation in these areas.

The focal spot size of one of the holographically produced zone plates was determined by a knife edge scan at the same wavelength [20]. The measurements showed a spot size of
290 nm which is comparable to both the recorded outermost zone width (260 nm) and the diameter of the pinhole (300 nm) used in fabrication.

Further reduction in the pinhole size has resulted in the improvement in the smallest zone width of the zone plate. Pinholes down to 100 nm diameter (Fig. 4, inset) have been fabricated in absorber films with thickness up to 300 nm. The zone plates fabricated with such pinholes have smallest zone with half of the diameter of the pinhole itself. The small number of zones seen in these images is due to the fact only the central part of the diffracted beam was used due to the low transmittance of the pinhole and the membrane in this case.

![Fig. 4. SEM image of the micro-zone plate patterns recorded on chemically amplified resist. The outer zone width is comparable to half of the pinhole size. (inset) SEM image of the pinhole with Au thin film on the top used for the fabrication of the zone plates.](image)

4. Discussions

4.1 Intensity modulation and diameter of the zone plate

Fringe visibility or modulation is one of the critical factors in interference lithography that affects the printability of a fringe pattern. It is defined \[ \mu = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \]
where \( I_{\text{max}} \) and \( I_{\text{min}} \) denote the local fringe intensity maximum and minimum, respectively. The success and quality of photoresist patterning depend on the modulation. A binary structure can usually be recorded in common photoresists when this is above 50%. In order to understand the fringe modulation in the current pinhole holography scheme, we again consider the far field intensity distribution of the light diffracted by the pinhole which is given by the Airy function

\[ I_d(r, z) = \left( \frac{\pi a^2}{\lambda z} \right)^2 \left( 2J_1(k a r / z) \right)^2 \]

where \( a \) is the pinhole radius and \( k = \frac{2\pi}{\lambda} \). Here we have assumed that the incident light has unity intensity and the pinhole is in a thin opaque membrane. The transmitted plane wave intensity is simply calculated as

\[ I_t = \exp(-2\beta k \Delta t) \]

where \( \Delta t \) is the thickness of the membrane. The local fringe modulation \( \mu(r, z) \) is given by

\[ \mu(r, z) = \frac{2I_t I_d}{I_t + I_d} \]

The fringe modulation is a function of both the radial position and the distance from the pinhole mask. First, let us consider the on-axis modulation \( (r = 0) \). This is at its maximum when the two interfering beams have equal intensity, i.e. \( I_t = I_d \). The maximum modulation is obtained at the distance \( z_0 \), given by

\[ z_0 = \frac{\pi a^2}{\lambda e^{\frac{\pi a^2}{\lambda z}}} \]

The modulation (for small angle, \( NA \approx r/z \)) is plotted as a function of the numerical aperture for \( z = z_0 \) in Fig. 5(a). The \( NA \) is normalized to \( NA_0 = 1.22 \lambda / d \) which corresponds to the first minimum in the Airy distribution. The modulation is fairly flat for small NA and it diminishes at the minimum of the Airy function, as expected. If we consider a threshold (approximately 50%) for modulation in order to achieve a binary pattern recording on a resist
film, the effective diameter as well as the outermost zone width of the zone plate is defined by this threshold rather than the 1st minima of the Airy function.

The modulation is shown in the contour plot in Fig. 5(b) as a function of the normalized distance from the pinhole and the normalized radial distance from the optical axis. We note that the only parameter controlling this plot is the attenuation by the absorber material of the membrane given by \( \exp(-2\beta k_{\Delta t}) \). The particular plot shown in Fig. 5b is calculated for an attenuation factor of 20,000. Changing the wavelength or the pinhole diameter will have no effect on this plot as these effects are already taken into account by the normalized parameters along the two axes. As this contour plot indicates, there is a wide region of space (shown white in Fig. 5(b)) available with large enough modulation to allow lithographic printing of a zone plate within the first Airy lobe. In general, increasing the attenuation factor moves the region where the modulation is high enough towards larger \( z \) and also towards the Airy minimum. Therefore, given a certain pinhole diameter, in order to print larger diameter or higher resolution zone plates it is in general necessary to attenuate the plane wave more strongly, i.e. by using a thicker absorber.

The two dotted lines in the plot indicate the positions of the first Airy minimum, corresponding to the numerical aperture \( NA_0 \). In order to print a FZP with the highest resolution possible one would like to print as close to the Airy minimum as possible. The contour plot indicates that this is possible by working at smaller \( z \). Based on our calculations we estimate that it should be possible to print zones at 0.85 \( NA_0 \) in which case the outermost zone width of the printed FZP will be approximately equal to the radius of the pinhole. Going to larger recording distance \( z \), will yield larger diameter zone plates albeit with somewhat reduced resolution. We also observe that all the zone plates printed in the space shown in this contour plot will have their focus at the origin of the plot, i.e. at the position of the pinhole.

4.2 Size and thickness of the pinhole: transmission and phase aberration

The outermost zone width of the FZP produced with the present method is related to the pinhole diameter. Therefore one of the main questions that need to be addressed is how far the pinhole diameter can be reduced to achieve smaller outermost zone widths. The treatment above does not take account of the fact that a pinhole is not a point source; rather it is a cylindrical-shape hole in a material layer of certain thickness. To understand the propagation of EUV radiation through a cylindrical pinhole opened in a gold film, we simulated the electromagnetic field propagation in such a structure using a finite difference time domain (FDTD) algorithm (EMExplorer® package [24]). A similar treatment was reported by Goldberg et al. [25] in the context of an EUV point diffraction interferometer. The field is
simulated for different pinholes ranging in diameter from 200 nm down to 20 nm. The incident field is linearly polarized with unit amplitude. The optical constants of the material were chosen for $\lambda = 13.5$ nm.

The component of the calculated Poynting vector along the direction normal to the Au film is shown in Figs. 6(a)–6(d) in a cross sectional plane going through the axis of the pinhole. The images demonstrate that as the pinhole size goes below the critical diameter, essentially unhindered propagation is replaced by a strong decay. In Fig. 7, the transmitted power is shown as a function of the pinhole diameter. Above a certain diameter (50 nm in the present case) the power is proportional to the cross-sectional area of the pinhole whereas for smaller pinholes it goes down sharply. This can be understood as the behavior of the pinhole as a waveguide with a small refractive index step and lossy walls. For such a cylindrical waveguide, the critical diameter for sustaining a propagation mode is given by $\sim \lambda/2\sqrt{2\delta}$ which is equal to 15 nm for a cylindrical waveguide in Au at $\lambda = 13.5$ nm [26]. The sharp reduction in the transmission defines the limit for the smallest diameter that can be used in our holographic approach for a given wavelength and the choice of absorbing material. Modest gains in resolution can be realized by selecting a favorable wavelength and a material but a general limit of approximately 10 nm holds [26].

Fig. 7. Outward energy flow at the exit plane of the Au layer normalized to the pinhole area is plotted against the pinhole diameter ($d$). A sharp deviation from proportional behavior (flux $\propto$ area) for pinholes with small diameters is observed.
So far we have assumed that the beam transmitted by the pinhole has a spherical wave front at the recording plane as predicted by the Airy equation. However, in reality the intensity and phase of the field at the exit plane of the pinhole differs from the uniform distribution considered in the derivation of this equation. Moreover the finite distance at which the recording is performed may have an influence on the exact shape of the wave front which determines the position of the printed Fresnel zones. Therefore we numerically calculated the phase front behavior of the field radiated by the cylindrical pinhole. The exit field distribution (found by the FDTD method mentioned above) is propagated to the image plane using a Huygens-Fresnel kernel [21]. The component of the electric field parallel to the polarization incident radiation, when propagated to the image plane (z = 100 μm) provides the phase front distribution with required accuracy [27, 28]. The deviation in the phase front from an ideal spherical phase front is fitted to a series of Zernike polynomials [29]. The first four lowest-order contributions (piston, tilt and defocus) that arise from the coordinate system transformation are removed from the calculation and the residual part is taken into consideration. The deviation of the wave front from an ideal spherical shape for four different pinhole diameters above 50 nm cut-off is shown in Figs. 8(a)–8(d). The lateral scale of the plots is normalized to the first Airy minimum (NA₀) for the corresponding pinhole diameter. We have found that the maximum error in each case is well within the acceptable limit (<<λ/4) for a zone plate construction [3] and therefore we conclude that wave front distortion is not a concern for this technique.

![Fig. 8. Residual optical path difference (OPD) from an ideal spherical wave at the image plane (z = 100 μm) for different pinhole diameters.](image)

4.3 Finite longitudinal coherence

As we have discussed above, the resolution limit of the printed FZP is determined by the first minimum in the Airy function (Fig. 5(b)). This diffraction limit ultimately defines a conical shape region in space inside which zones of a FZP can be recorded. This region whose diameter is given by 2.44λz/d is schematically shown in Fig. 9.

The coherence length given by λ²/Δλ (Δλ being the width of the spectral distribution of the incident radiation) limits the optical path length difference that is allowed between the spherical and plane waves. This condition limits the number of zones that can be printed to λ/Δλ. Hence the maximum diameter D of the printed zone plates can be estimated as
This longitudinal (or temporal) coherence limited region is also schematically shown in Fig. 9. The transition occurs at \( z = d^2 / [4.88 \Delta \lambda] \). Beyond this distance, the diameter and the resolution of the printed FZP is controlled by the coherence length rather than diffraction. A larger diameter or higher-resolution FZP can be realized by using a narrower spectral width beam, for example by filtering the beam with a monochromator, but this comes at the expense of reduced flux.

4.4 Printing a desired FZP

Now, let us consider the parameter space involved in the fabrication of an FZP with the described technique to understand the practical limits and possible trade-offs. First, the FZP that we aim to fabricate can be defined by its diameter \( D \), outermost zone width \( \Delta r_N \), and the wavelength, \( \lambda \), at which it is going to be used. Here, we assume that the same wavelength is also used in the holographic fabrication procedure. In addition, the beam that illuminates the pinhole has a given intensity \( I_0 \) and the photoresist used in recording the interference pattern requires an exposure dose \( D_0 \) (usually given in units of mJ/cm\(^2\)). The absorber (attenuator) material in which the pinhole aperture with radius \( a \) is opened has an absorption coefficient \( 2\beta k \) and thickness \( \Delta t \).

Based on the FZP specifications and the beam and material parameters given above we can design a pinhole mask and estimate the required exposure time to record the desired FZP. First, we assume that the fabricated zone plate diameter is going to cover a radial range going up to 85% of the radius of the first Airy minimum, i.e. we require a 50% fringe modulation up to this point. From Eqs. (1), (2) and (3) we find out that the pinhole radius is equal to the outermost zone width, i.e.

\[
a = \Delta r_N.
\]  

Note that this equation also sets an upper limit for the pinhole radius \( a \). With a smaller radius pinhole one can print an FZP with the same outermost zone width but this will come at a price of reduced intensity and longer exposure time. Now using again Eqs. (1), (2) and (3) and
requiring the modulation to be 50% at $NA = 0.85NA_0$ we find the required absorber thickness as

$$\Delta \tau = \frac{1}{2\beta k} \ln (12.5s), \quad (7)$$

where $s$ is the ratio of the area of the desired FZP plate to that of the pinhole, i.e. $s = D^2/4a^2$.

The required exposure time $\tau$ is found as

$$\tau = \frac{0.625}{s} D_\Delta I \quad (8)$$

Here we observe that the required thickness of the absorber and the exposure time only depend on the area ratio $s$. Usually, one is limited to a certain exposure time for practical reasons. If the exposure time is taken as the main constraint we know the ratio, $s$ from Eq. (8), which means that we are left with a trade-off between FZP area and resolution. Using the same exposure time we can choose to print a high resolution FZP with a small diameter. We note that the ratio $s$ is related to the number of zones $N$ through the equations $N = D/4\Delta r_N$ and Eq. (6). Therefore, we can also conclude that the number of zones that can be printed within a given exposure time $\tau$ is determined by the following equation, irrespective of the resolution:

$$\tau = 25N^2 \frac{D_\Delta}{I_0} \quad (9)$$

5. Conclusions

The holographic approach described in this article provides means for fabricating FZPs with a sufficiently high resolution for most X-ray microscopy applications. One of the most important features is the absence of pattern placement (or zone position) errors. Production of FZP patterns with a zone width as small as 50 nm have been experimentally demonstrated.

Basic and practical limits on the performance of this technique in relation to the parameters of the obtained zone plates have been derived and discussed. The fundamental limit on resolution is imposed by the limited refractive index contrast found in the X-ray region between different materials and vacuum. This implies that below a certain pinhole diameter, transmission through the pinhole aperture diminishes. This limit on the minimum usable pinhole diameter directly translates into a minimum zone width obtainable with this technique. The spectral width of the illuminating beam determines the maximum number of zones that can be printed because of the loss of coherence between the interfering spherical and plane waves beyond a certain optical path length difference. And finally, the three quantities, beam intensity, photoresist exposure dose sensitivity and practical maximum exposure time, place together another limit on the maximum number of zones that can be printed. Through improvements in light sources and photoresist materials the technique can be used to print larger and higher resolution zone plates.

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