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A new application for X-ray lithography: fabrication of blazed diffractive optical elements with a deep phase profile

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ABSTRACT

The use of the X-ray lithography to produce blazed diffractive optical elements (DOEs) is described. The proposed method allows one to make highly efficient blazed DOE with a deep phase profile (ten wavelengths and more) using a single X-ray mask with a binary transmission pattern. Unlike the well-known multilevel DOEs, blazed ones do not involve fabrication and aligning of a set of masks. DOEs with a profile depth of 10 μm and more and zone sizes of down to 1 μm can be obtained due to the short wavelength and high penetrability of X-rays.

The first experimental samples of blazed DOEs with a 10 μm-height profile — lenses and gratings — were fabricated by X-ray lithography with synchrotron radiation using the X-ray masks, prepared in accordance with the pulse-width modulation algorithm. Diffraction efficiency for lenses was measured for white light. It is higher than 80% for the central part of the lenses (inside a 10 mm diameter) and about 60% for an area of 20 mm diameter.

Keywords: X-ray lithography, synchrotron radiation, diffractive optical elements, deep phase profile.

1. INTRODUCTION

Diffractive optical elements (DOEs) are important components of modern optical systems. Today DOEs have a wide application in mass produced optical systems, such as laser players, printers, sensors, etc. Until now, the applications were limited mainly by monochromatic radiation.

Recent studies[1,2] have shown the possibility of white light conversion by high-order DOEs (kinoforms) with a continuous profile. Such DOEs represent the profiled diffractive gratings with a profile depth of up to several tens of a wavelength (i.e., 10-20 μm for the visible range) and a complex continuously varying profile. It is expected that progress in diffractive optics is connected with wide practical application of such elements. Their potential capabilities essentially depend on the fabrication technology, which should provide maximal diffraction efficiency and signal-to-noise ratio for transformed optical signals. The main problem in fabrication of diffractive optical elements for polychromatic light is connected with the formation of the deep phase profile.

Since the early days of diffraction optics, many methods for producing of DOEs have been developed. However these methods are applied to the fabrication of conventional DOEs with an optical depth of about a wavelength. The use of X-ray lithography[3] offers the possibility of obtaining diffractive structures with a profile depth of 10 - 100 wavelengths in the visible range, because of the short wavelength and high penetrability of X-rays and the low level of scattering inside the X-ray resists.

This paper presents the results of a novel one-step method for fabrication of highly efficient DOEs with a deep continuous profile. The method is based on incoherent spatial filtering of X-ray radiation passed through an X-ray mask. The basic characteristics of the X-ray halftone method of DOE fabrication are described, and the first results of the DOE fabrication are shown.

2. PRINCIPLES OF DOE FABRICATION

The fabrication problem of a phase-only DOE with the transmission function

$$T(x) = exp[i\cdot\varphi(x)] \qquad (1)$$

is solved by forming a relief $h(x) = \varphi(x) / [k\cdot(n-1)]$ in the substrate, where $k = 2\pi/\lambda$, λ is the wavelength, and n - the refractive index of the substrate.

As is known from the theory of lithography,[4] when positive resists are exposed to radiation of intensity $I(x)$, the thickness of a layer after development is: $h(x) = D - \gamma\cdot I(x)$, where D is the thickness of the initial resist layer, and γ is a function of exposure duration, development time, and other resist parameters. If the distribution intensity $I(x)$ is proportional to the phase function $\varphi(x)$, a DOE profile in the resist layer with a transmission function $T(x)$ is formed.

One way to make such a intensity distribution is to use a gray-tone mask with the transmission function $U(x) \approx \varphi(x)$.[5] There are some technical difficulties, however, in fabricating such a mask for X-ray radiation. A cutting technique allows one to produce very high-quality DOEs but unfortunately only with a simple circular structure.[6] Multilevel technology [7] requires a large set of masks for forming numerous discrete phase levels and is difficult to the realize practically.

According to the proposed technique, a continuous phase profile is formed by X-ray lithography with the use of a pulse-width modulated mask. Such a halftone technique (recently successfully applied to DOE fabrication in the optical range[8]) enables one to replace a gray-tone mask with a binary one. A halftone process can be interpreted as a coding technique. It converts the function of the DOE phase distribution in Eq. (1) into a binary image $B(x) = V[\varphi(x)]$. The operator V converts the "gray-tone" function $\varphi(x)$ into a binary one $B(x)$. This function is the X-ray mask transmission function.

The scheme of the lithographic process that can be applied to this technique is depicted in Fig.1a. An X-ray mask is illuminated by X-rays produced by an electron storage ring. The distance from the X-ray source to the mask is $L \approx 10\ m$. The resist layer is exposed at a distance d from the mask. This gap between the X-ray mask and the resist layer is large enough (several tens of millimeters) to smooth the pulse-width modulated pattern of the X-ray mask. The quality of the smoothing depends on distance, the light source aperture, and its spectrum.

The source of the synchrotron radiation provides X-rays in a wide spectral range, $0.6 < \lambda < 1.2\ nm$; it has a Gaussian intensity distribution with $\sigma_x \approx 0.5\ mm$. Due to these parameters, we can use the geometrical model for the calculation of intensity distribution behind the mask as the first approach. In this case, the intensity distribution in the photoresist plane is defined as a convolution of the impulse response for a long narrow slit R(x) and the mask transmission function $B(x)$: $I(x) = R(x) \otimes B(x)$. In the geometrical model, the impulse response is defined by a projection of the source intensity distribution into the image plain: $R(x) = exp[-(mx)^2 / \sigma^2]$, where $m = d/L$ is the projection coefficient (scale factor). In Fig. 1b-e, the intensity distributions of X-rays are shown for different distances from the mask. The mask transmission function is a pulse-width modulated function that corresponds to the saw-tooth function with period T. One can see the intensity distribution at the distance d_4 is fairly close to the saw-tooth function.

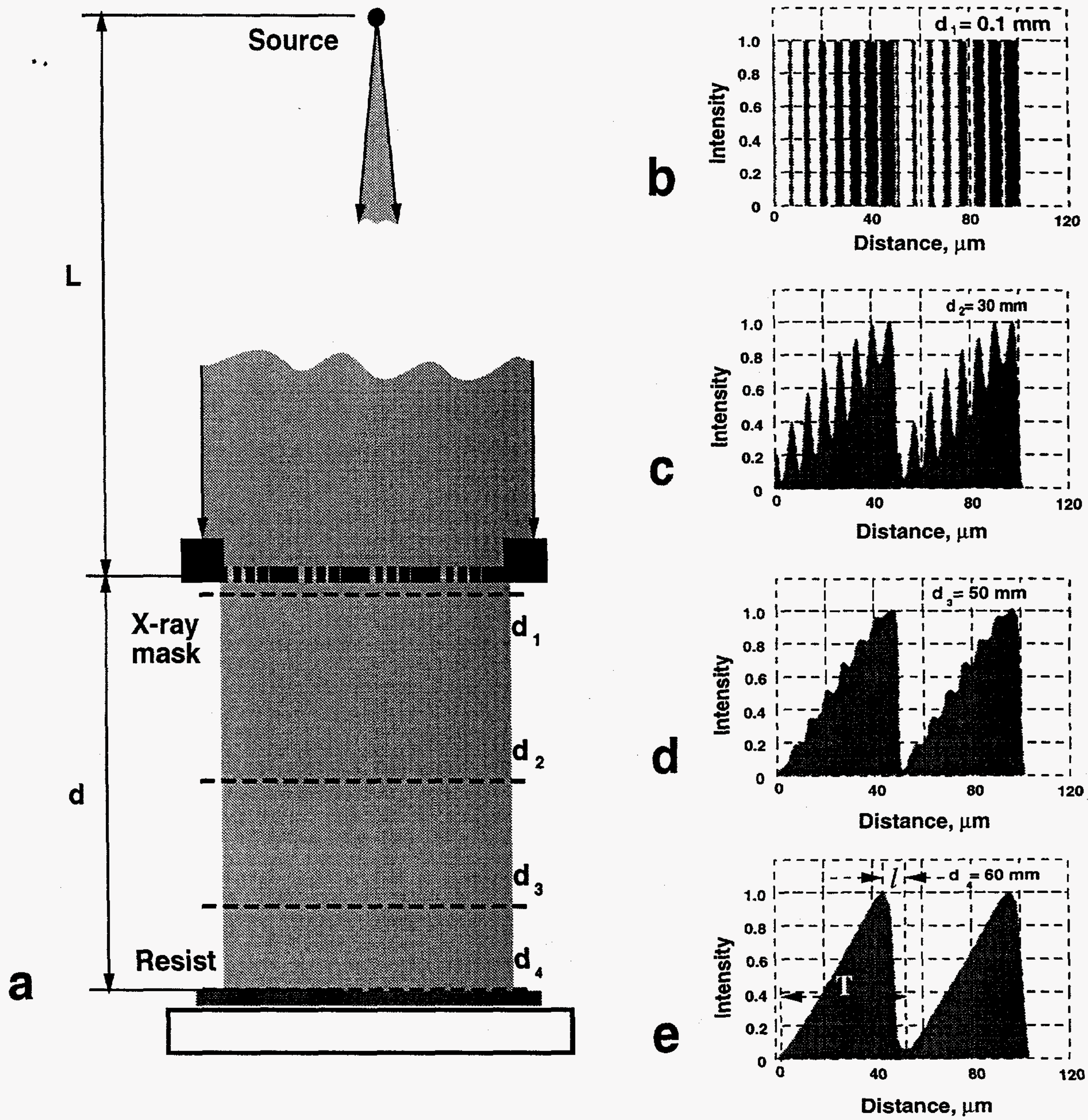

Fig.1. X-ray lithography setup scheme *(a)* for fabrication of continuous relief diffractive optical elements by means of the pulse-width modulated rastered mask. Results of the simulation of intensity distributions for the X-ray radiation in the planes located at distances d_1=0.1 mm *(b)*, d_2= 30 mm *(c)*, d_3=50 mm *(d)* and d_4=60 mm *(e)* behind the X-ray mask.

The finite number of pulses leads to the difference between the intensity distribution and the desired function and thus limits the diffractive efficiency of the blazed grating. In order to achieve high efficiencies, a sharp triangular profile is needed to minimize the incorrectly blazed area of the facet as much as possible.

The losses of light energy on this facet can be evaluated as $2l/T$, where l is the length of the incorrectly blazed section of a facet (close to the period of raster stripes) and the coefficient 2 is introduced according to the scalar theory. Thus, the diffractive efficiency of the blazed grating is $\eta = 1 - 2l/T$.

2.1. Masks for diffractive optical elements

We have fabricated a 10th order F/7 diffractive lens (phase zone plate) by exposing directly a polymethylmethacrilate (PMMA) substrate to illustrate an application of X-ray lithography for the fabrication of blazed DOEs. The edges of the zones are located at distances r_k from the center: $r_k^2 = 2k f_0 \lambda_0 p + k^2(\lambda_0 p)^2$, where k is the integer defining the order of the zone, f_0 is the principal focal distance, λ_0 is the central wavelength of incident light, and p is an integer defining the working diffractive order number. A linear approximation of the phase function $\varphi(x)$ for the outer zones and a parabolic approximation for the central zone were used. The algorithm of the pulse-width modulation (PWM) was applied to convert the saw-tooth phase function into a binary one.

In the PWM method, the discretization period T_d of the raster stripes repetition is constant, and their widths W_i are proportional to the coded values $\varphi(x_i)$ in the discretization points i:

$$W_i = T_d\{0.5 + P[\varphi(x-iT_d) - 0.5]\}.$$

Here, i = 1,2,3... is the stripe number, $P = (W_{max} - W_{min}) / (W_{max} + W_{min})$ is the modulation depth, and W_{max} and W_{min} are the maximum and minimum pulse widths over the period of a kth zone. The zone plate has circular symmetry; therefore a raster derived from the circular rings with width W_i was used for the binarization.

Masks with a two-grade transmission pattern can be easily fabricated by means of conventional e-beam or laser pattern generators. At the first step, a primary mask for the diffractive lens was made by direct pattern recording with the use of a focused laser beam (0.8 µm) of a precise circular laser pattern generator (CLPG). The method of primary mask fabrication is based on the effect of thermo-chemical changes in a thin chromium film under the effect of intense laser radiation.[9] The minimum width of the mask raster circular stripes was defined by the CLPG spatial resolution and was equal to W_{min} = 1.2 µm.

The X-ray masks were prepared using the conventional lithography technique to replicate the primary mask pattern into a 1-µm-thick resist layer covering a silicon wafer with a layer of 2-µm-thick silicon nitride on the planar side. Then, a 0.6-µm-thick layer of gold (as an X-ray absorber) was electroplated inside the resist pattern. Finally, after removing the resistive mask, a 2 µm-thick silicon nitride membrane, transparent to X-rays, was formed by etching the silicon wafer. The X-ray masks were fabricated at the Center for X-ray Lithography (University of Wisconsin-Madison).

2.2. Fabrication of diffractive optical elements

The ES-1 beamline at the ALADDIN storage ring of the University of Wisconsin-Madison was used to expose PMMA sheets through the X-ray mask with a gap of about 40 mm between the mask and resist. The exposure unit was scanned vertically to expose the total area. X-ray exposure doses in the range of 8 - 15 J/cm^2 were used. Then lenses and gratings with a blazed profile of about 10 µm deep were formed in the development process. A diffractive lens created in the PMMA sheet (focal length F = - 200 mm, diameter ∅ = 30 mm) with a blazed profile of 10 µm deep is shown in Fig. 2.

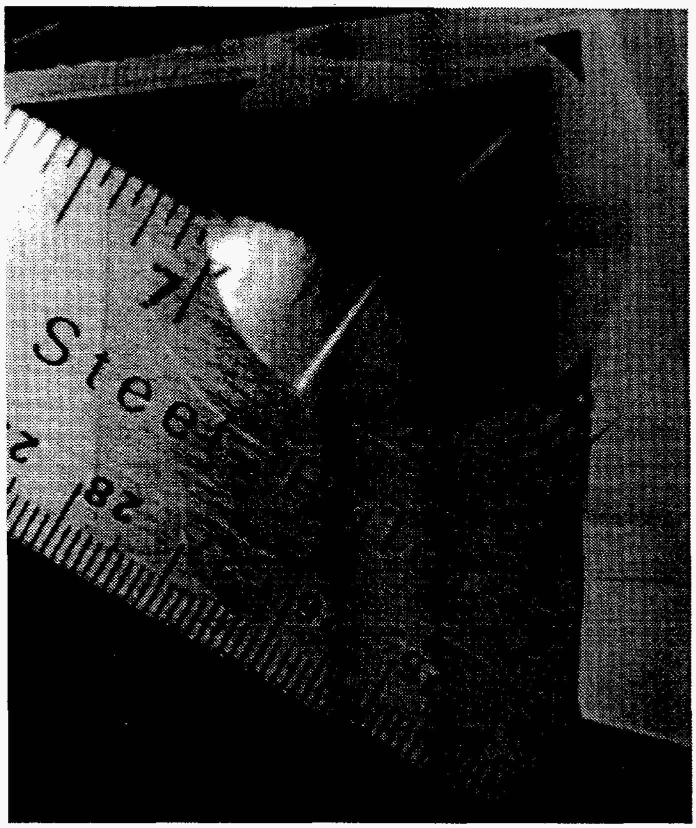

Fig.2. The diffractive lens replicated in a PMMA sheet (focal length F = - 200 mm, diameter ∅ = 30 mm) with a blazed profile of 10 μm depth.

3. RESULTS

Deep-phase profiled blazed optical elements fabricated by the X-ray lithography method are demonstrated. A blazed diffractive lenses (kinoform) with 200 mm focal length and 30 mm in diameter, blazed diffractive gratings with a 100 μm period, and a blazed diffractive mirror with a 100 mm focal length were produced. A typical profile of a part of the kinoform lens formed in a PMMA sheet measured by the *Alpha Step 200* profilometer is shown in Fig. 3. The size of zones varies from 70 μm (periphery) to 1 mm (central part). The profile looks slightly wavy, which means that the gap between mask and resist plane was slightly smaller than needed. With the smaller gap value, the relief became more wavy, a larger gap provided smoothening of waves due to a raster period, while for a more wide gap the saw-tooth shape of the lens zones is smoothed.

Preliminary measurements demonstrate apochromatic properties for these diffractive mirrors and lenses. The focusing properties of lenses for monochromatic light were studied. The location of the diffraction foci for different orders and the intensity distribution near the optical axis were measured. Some of these results are plotted in Fig.4: the region of the light energy concentration is highlighted near the coordinate with optical power $D=1/F=5m^{-1}$ for the wavelength region from 450 to 650 nm. Foci locations of different orders, calculated with equation for the foci of a multiorder diffractive lens, are shown by solid lines. Experimental values are represented by filled dots. In the visible region, the lens works within 9 - 14 orders of diffraction. The first samples of the lenses give a rather high level of a diffuse light, which is due to roughness of the resist surface after the development process. Diffraction efficiencies for the lenses were measured for white light. They are higher than 80% for central part of lenses (inside a 10 mm diameter), about 60% for an area of 20 mm diameter and about 35 - 40% for the total lens area (30 mm diameter).

4. CONCLUSION

Verification of the capability to make blazed DOEs with a deep phase relief was done using an X-ray lithography method. Blazed DOEs with the depth of phase profile of about 10 μm were fabricated.

It has been shown both theoretically and experimentally that halftoning technology using a single mask allows one to fabricate DOEs of high diffraction efficiency (over 80%).

The limit of diffraction efficiency for a DOE fabricated with halftone and multilevel technologies is determined by the fabrication accuracy of the mask topology boundaries.

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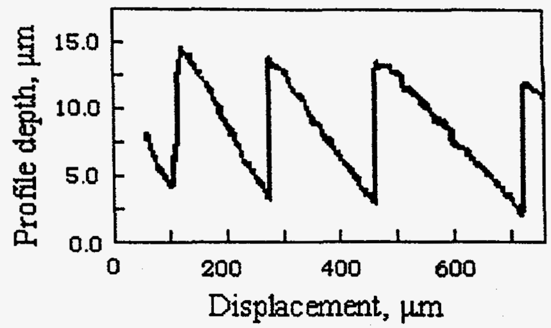

Fig.3. Example of a measured profile (3 periods) of the kinoform lens fabricated by X-ray lithography with the pulse-width modulation method.

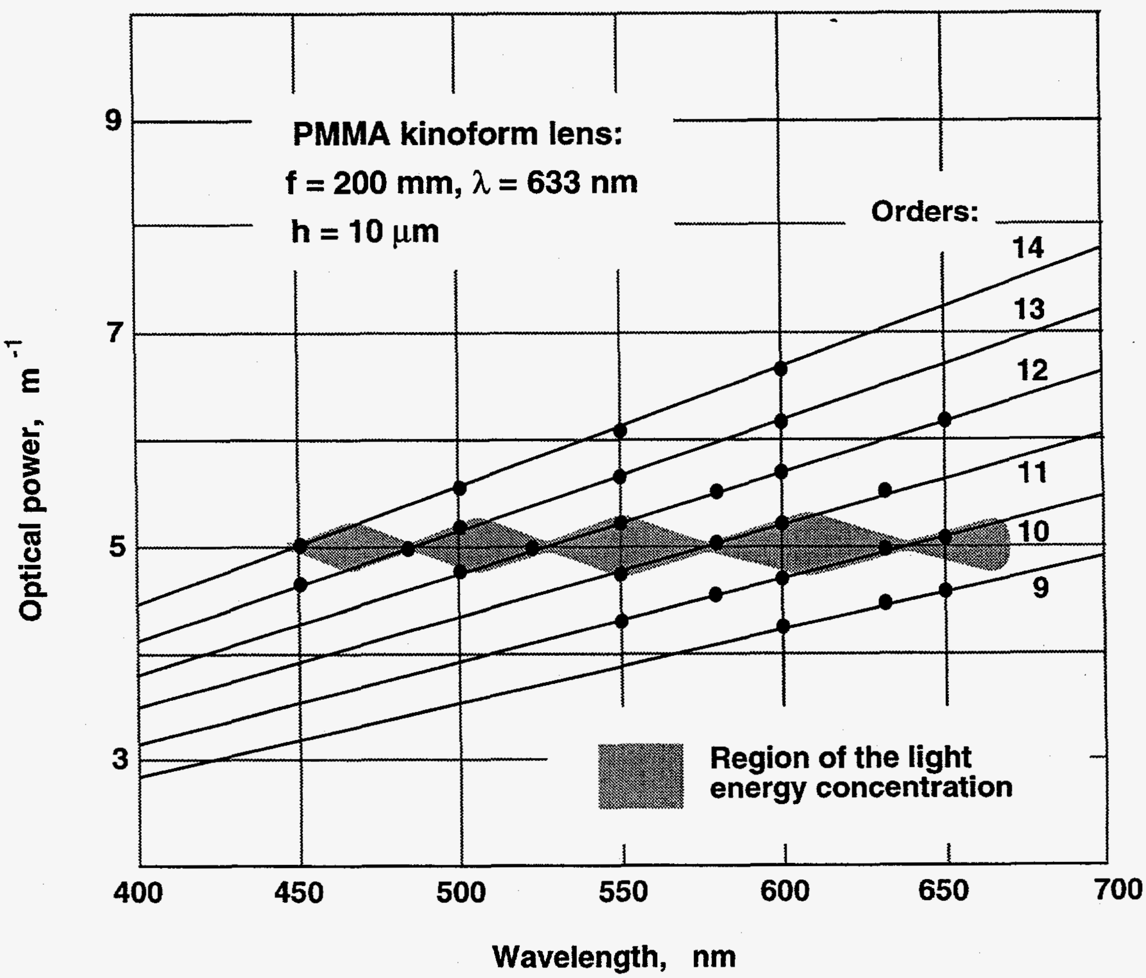

Fig.4. Dependence between an optical power (1/F) and a wavelength calculated for a common zone plate (solid lines) and measured for the blazed zone plate working at the 9-14th diffraction orders (points); the region of light energy concentration is hatched

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