Diffraction optical elements with deep profile manufactured by X-ray lithography

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Abstract

An X-ray lithography with synchrotron radiation was applied for formation of the Fresnel zone structure profile onto a curved surface of a refractive polymer lens to achieve multifocus properties of the lens. First prototypes of the hybrid refractive-diffractive lens were fabricated by such a way and their optical properties were investigated.

A blazed diffractive optical elements with deep continuous phase relief were fabricated using a pulse-width modulated X-ray mask, ones work well for white light.

Some possibilities for the creation of diffraction apochromatic optical elements are considered as well.

I. INTRODUCTION

Synthesis of apochromatic images by diffractive optical elements (DOEs) only comes across on a row of difficulties, main of which is a high chromatizm of axial diffractive lenses. It is possible to achromatize only an imaginary image by means of DOEs (1), so for the achievement of practical results one resorts to aksikon focusing (2) or uses a peripheral parts of an optical system pupil (3).

Single-element achromatic diffractive lenses (4, 5) attract attention of researchers recently. Firstly this idea was patented and formulated by Kovachev (6, 7). However, the results, obtained by him, lead to discussions and have not got sufficient attention in that time.

Addressing to “deep or high order kinoforms”, or so called “harmonic Fresnel lenses” (5), gives for calculation of optical systems a new, additional power of freedom, which can be used for optimization of optical systems.

Such DOEs represent themselves profiled diffractive gratings with complex continuously varying profile and with depth up to several tens of microns. However it is possible to produce only simple DOEs with circular structure by cutting technique (5). Multilevel technology (8), well known in diffractive optics, requires a set of tens masks and from 100 to 200 phase discrete levels, that non-realizable in practice.

Another way to form a DOE profile is based on incoherent spatial filtering of a periodic pulse-width modulated (PWM) mask spectrum combined with a conventional lithography process (9). This halftone method simplifies substantially the process of DOE fabrication because it does not involve fabrication and aligning of a set of masks. Diffractive lenses arrays with efficiency up to 85% were fabricated by means of using the only binary mask and projection lithography (10). However the depth of continuous profile of more than 2 - 3 μm cannot be obtained by this method because of considerable diffractive effects and scattering inside a resist layer.

The main problem in fabrication of diffraction optical elements for polychromatic light is connected with deep phase profile formation. The use of an X-ray lithography offers the possibilities to obtain a profile with a depth of 10 - 100 wavelengths of visible range (11). Another apparent advantage of X-ray lithography is its ability for synthesis of patterns with micrometer size elements onto curved surfaces. The appropriate diffraction structures with deep phase profile formed on plane or curved surfaces allow one to decrease the lens aberrations and solve the fundamental problem of diffraction optics, chromatism cancellation.

A combination an X-ray lithography method and technique of binarization for half-tone patterns allow one to fabricate blazed diffraction optical elements with a deep phase relief. This combination leads to considerable simplification of the fabrication procedure by means of using the only ordinary mask with two-grade transparency. The X-ray proximity exposure at large gaps acts as a low-pass spatial filter. This allows one to make diffraction optical elements with a profile depth of 10 μm and more, with zone sizes down to 1-2 μm. This is possible with X-ray lithography only, because of the short wavelength, high penetrability of X-rays and low level of its scattering. These optical elements are poly-chromatic and have efficiency high enough for white light. A large number of important applications that use a white light became accessible for diffraction optical elements with a deep continuous phase profile and high diffraction efficiency.

Today diffraction optical elements get a wide application in mass production optical systems, such as laser players, printers, cash registers, units for checking a code of articles and laser technology installations. In all these systems lasers are used as a source of radiation, having a narrow radiation spectrum. Creation of diffraction elements working with white light, promoted development of new applications, as it allows one to create achromats and apochromats by the only diffractive surface. It should be wait an appearance of laser scalpels, new diffractive glasses and artificial interocular lenses for eyes.

The aim of proposed work is to show possibilities of a deep X-ray lithography for creation single achromatic diffractive lenses and single-component hybrid elements.

II. DIFFRACTIVE APOCHROMATIC OPTICS

Spectral characteristics of diffraction lenses are essentially different from the ones of refraction lenses. An optical power of a refractive lens is:

$$f(\lambda) = [\, n(\lambda) - 1 \,] \times C \,,$$

where $n(\lambda)$ is the refractive index and C is the curvature of the lens surface.

The similar power for a diffraction lens is:

$$\phi(\lambda) = [\lambda / \lambda_0 \,]\, \phi(\lambda_0) \,,$$

where λ_0 is a design wavelength. The optical power of a diffraction lens is linear with wavelength.

A combination of refractive and diffractive elements allows one to compensate dispersion of an optical system and fabricate hybrid achromatic objectives for visible light. However, this way does not allow one to solve the problem of dispersion cancellation completely by the use of diffraction elements only.

The problem of extending the spectral range can be solved by fabrication of "deep" diffractive lenses. The phase difference of zones for a normal diffraction lens equals 2×π (or λ_0) and the zone radii are defined by the formula:

$$r^2_k = 2\times k\times\lambda_0 \times F_0 ,$$

where F_0 is a focus of the lens and k is a zone number.

For the lens with a deep phase profile the last formula transforms to:

$$r^2_k = 2\times k\times p\times\lambda_0\times F_0,$$

where p is integer and $p\times F_0$ is the focus length for the first diffractive order. If $p > 2$, the lens collects the light beams of several wavelengths at the same focal point, and, as a consequence, the creation of achromatic and apochromatic diffraction singlets for wide band of visible, IR and UV spectral ranges becomes possible.

The focus of this multi-order diffraction lens is defined by the expression:

$$F(\lambda) = p\times\lambda_0\times F_0/(m\times\lambda),$$

where m is the order of diffraction. Under the condition $(p\times\lambda_0)/(m\times\lambda) = 1$, the light beams with the wavelengths $\lambda = (p/m)\times\lambda_0$ will concentrate at the same focal point providing achromatic or apochromatic properties of the diffraction lens.

One of the important applications of diffractive elements is an interocular lens (artificial eye) with the qualitatively new properties. A proper diffraction structure formed on the surface of a usual refractive interocular lens provides bi- or multi-focus properties of the lens (12). Such a lens extends the accommodation depth of the eye by two or more times and does not require additional correction of sight by spectacles. Fabrication of hybrid bifocal interocular lens is the first step toward creation of a completely apochromatic diffraction lens.

For a hybrid interocular lens, the depth of diffraction structure profile on a spherical surface must be of order of a few micrometers. Exposure of polymer spherical microlenses by parallel intensive X-ray beams through an appropriate X-ray mask gives the possibility to fabricate diffraction structures with a required profile depth.

III. FABRICATION OF DIFFRACTION OPTICAL ELEMENTS

The unique peculiarities of the synchrotron radiation are a short wavelength λ of radiation in a combination with small angle divergence, wide spectral range and high intensity. That allows one to use synchrotron radiation to create DOEs with new and useful properties.

3.1. Diffraction pattern on spherical surface.

Diffractive structure formation on 3-dimensional surface is possible by lithography methods with the synchrotron radiation only. Sharpness depth (a gap between an X-ray mask and a resist layer) $D1 + d$ is defined by acceptable blur value W for microimage edges with a correlation $D1 + d \sim W2/\lambda$ (13). For example, if $W = 1\ \mu m$, $\lambda \sim 1$ nm, then $D1 + d \sim 1$ mm. Fig.1a shows exposure layout for spherical surface.

Thin film of X-ray resist can be used to cover surface of a glass lens or polymer material of a lens itself can be used as an X-ray resist. High intensity of synchrotron radiation allows one to perform X-ray exposure of single optical elements formed from polymethylmethacrylate (PMMA).

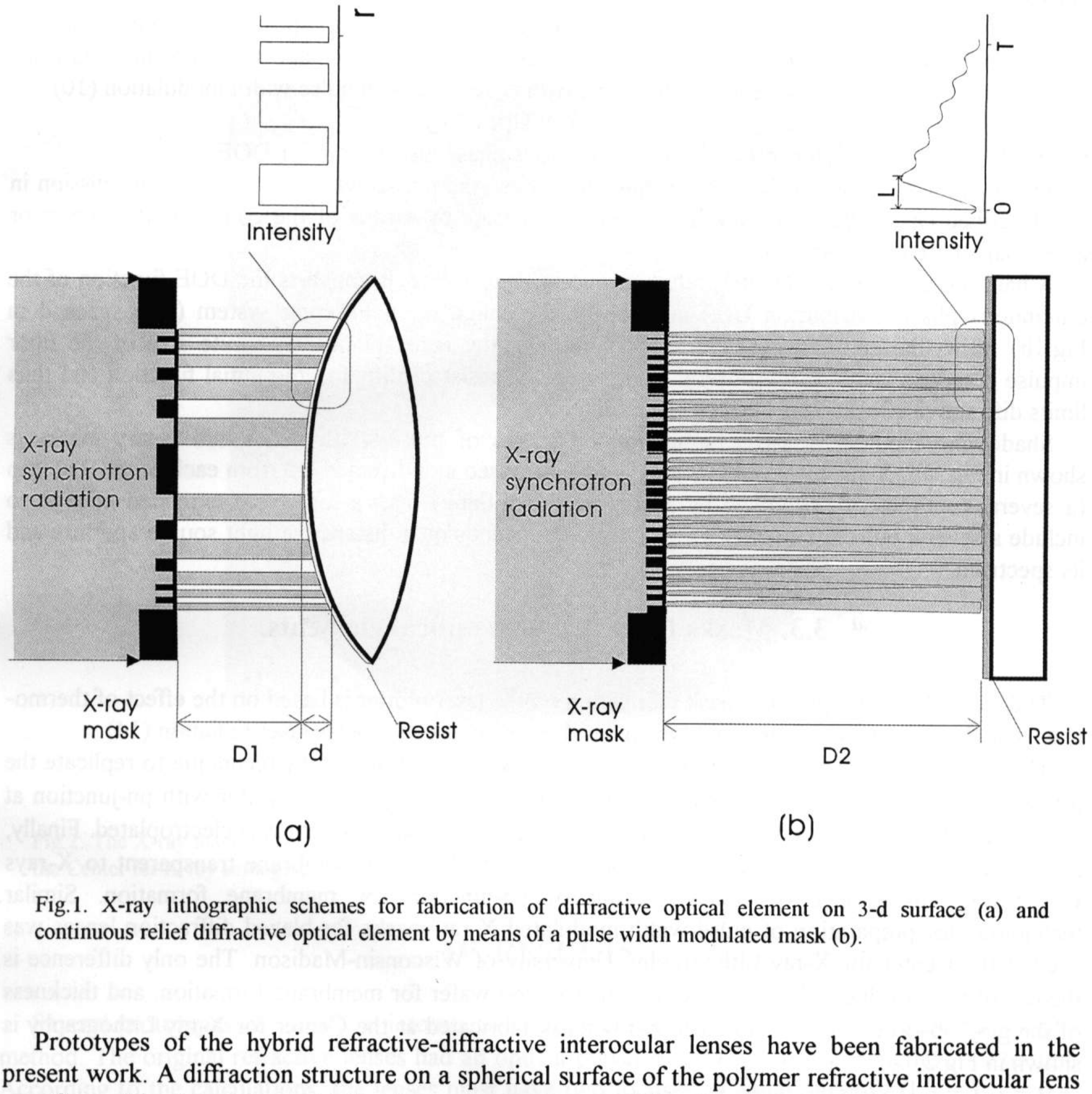

Fig.1. X-ray lithographic schemes for fabrication of diffractive optical element on 3-d surface (a) and continuous relief diffractive optical element by means of a pulse width modulated mask (b).

Prototypes of the hybrid refractive-diffractive interocular lenses have been fabricated in the present work. A diffraction structure on a spherical surface of the polymer refractive interocular lens was formed in three steps. At the first step, a primary diffraction lens mask was made by direct pattern recording with the use of a narrow laser beam (0.8 μm) of a precise laser-writing system. At the second step, the X-ray mask of the lens was fabricated by replication of the primary mask pattern. The last step - fabrication of a diffraction microlens structure in a PMMA interocular lens was carried out using X-ray synchrotron radiation (Fig.1a). The use of X-ray lithography at the last step allowed one to avoid a contact between the mask and the lens and replicate the mask pattern onto a spherical surface practically without geometrical distortion.

3.2. DOE with deep continuous profile.

Increasing of pattern edge blur W is occur when gap D2 between mask and resist layer is enlarged ($W \sim (D2\cdot\lambda)1/2$). If we choose D2 value so that blur value W will be greater than distance T between neighborhood transparent elements of mask (discretization period), then beams of radiation will intermix in a resist plane for these elements, as shown in Fig.1b. It is possible to obtain a desired (saw tooth) intensity distribution for exposing radiation in a resist plane by choosing a law for alteration of size of mask elements l_i, for example in according with pulse width modulation (10):

$$l_i = T\cdot[0.5+P\cdot U(x-i\cdot T)],$$

where P is the modulation depth, U(x) is a continuous phase distribution for DOE.

This method (halftone technique) enables one to use the masks with a two-grade transmission in the described case. The binary masks can easily fabricate by means of the conventional e-beam or laser image pattern generators.

A halftone process can be interpreted as a coding technique. It converts the DOE function of the continuous phase distribution U(x) into the binary image B(x). Filtering system (free space d in Fig.1b) forms the smoothed intensity distribution in the resist plane. The finite size of the filter impulse response leads to the difference between the resist profile and the initial function and thus limits diffractive efficiency of the blazed grating (10).

Shadowing method of DOE fabrication by means of pulse-width modulated binary masks is shown in Fig. 1b. X-ray mask and resist layer are disposed at a distance D2 from each other. The gap (a several centimeters) is defined by averaging (smoothing) over a local area extended enough to include a several pulses. The quality of smoothing depends on a distance, a light source aperture and its spectrum.

3.3. Masks for diffraction optical elements.

The technology of a primary mask fabrication on the laser plotter is based on the effect of thermo-chemical changes in thin chromium films under their exposure to intense laser radiation (14).

The X-ray masks were prepared using a conventional photolithography technique to replicate the primary mask pattern into a 1.6 μm thick resist covering a p-type silicon wafer with pn-junction at planar side. Then, a 1.5 μm thick X-ray gold absorber of the mask pattern was electroplated. Finally, after removing the remaining resistive mask, a 2 μm thick silicon membrane transparent to X-rays was formed using electrochemical etching of pn-junction for membrane formation. Similar technology for preparation of pulse-width modulated X-ray masks for blazed diffraction lenses was used at the Center for X-ray Lithography, University of Wisconsin-Madison. The only difference is the use of a 2 μm thick silicon nitride film on a silicon wafer for membrane formation, and thickness of the gold absorber was 0.6 μm. The X-ray mask fabricated at the Center for X-ray Lithography is shown in Fig.2.

3.4. Exposure of diffraction optical elements.

The X-ray lithography station at the VEPP-3 storage ring in the Budker Institute of Nuclear Physics was used for performing the X-ray mask pattern replication onto a curved surface of a refractive polymer lens and the used wavelength range of synchrotron radiation was 0.3-0.8 nm (15). Under conditions of appropriate exposure dose a Fresnel zone structure was formed in the polymer lenses without any subsequent treatment to achieve multifocus properties of the lens.

The ES-1 beamline at the ALADDIN storage ring of the University of Wisconsin-Madison was used to exposure PMMA sheets through the pulse-width modulated X-ray mask with gap of about 40 mm. Then blazed lenses with a profile depth of about 10 μm were formed in the development process.

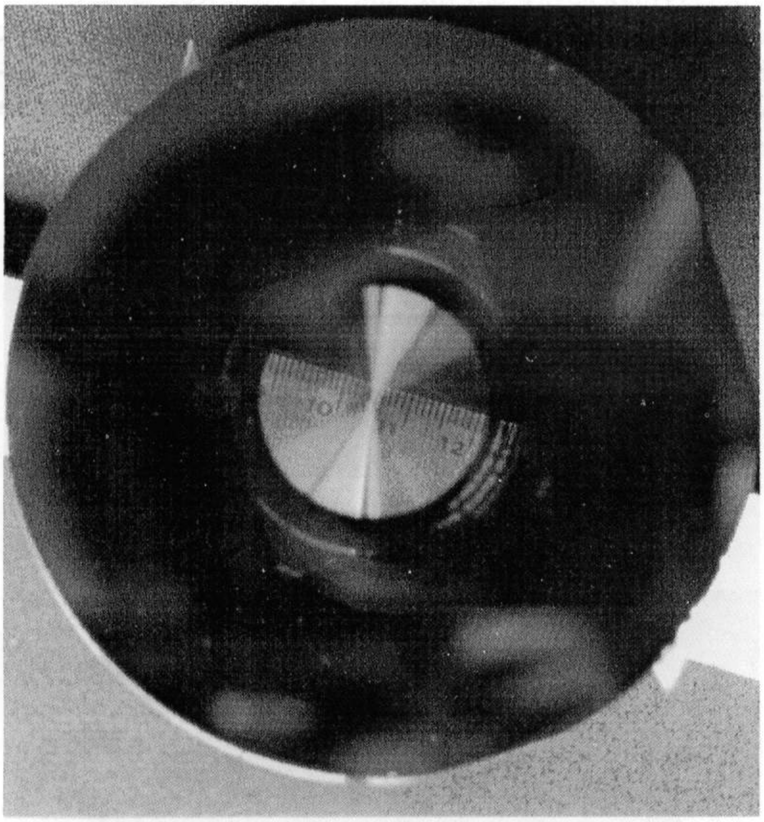

Fig.2. The X-ray mask with 0.6 μm-thick gold absorber on 2 μm-thick silicon nitride membrane fabricated at the Center for X-ray Lithography, University of Wisconsin-Madison.

IV. RESULTS

Several prototypes of multifocal interocular lenses have been fabricated by the X-ray lithography method. The original refractive lenses had an optical power $\phi = 24\ \mathrm{m}^{-1}$ at wavelength $\lambda = 0.63$ μm. According to the calculations, the lenses must have two focuses of equal intensity ($I_{-1} = I_{+1} = 0.4$, $I_0 = 0$) at the depth of the lens diffraction profile of $h = 1.9$ μm, and must have three focuses ($I_0 = I_{-1} = I_{+1} = 0.27$) at $h = 1.215$ μm as shown in Fig.3. Investigation of the fabricated lenses in visible light shows that the obtained values of the focal intensities are in a good agreement with the calculated ones within the measurement accuracy of about 5 %. The multifocal interocular lens with focal lengths $F_{-1} = 14.1$ mm, $F_0 = 13.2$ mm, $F_{+1} = 12.2$ mm in the air and with the diameter ∅ = 5 mm is shown in Fig 4.

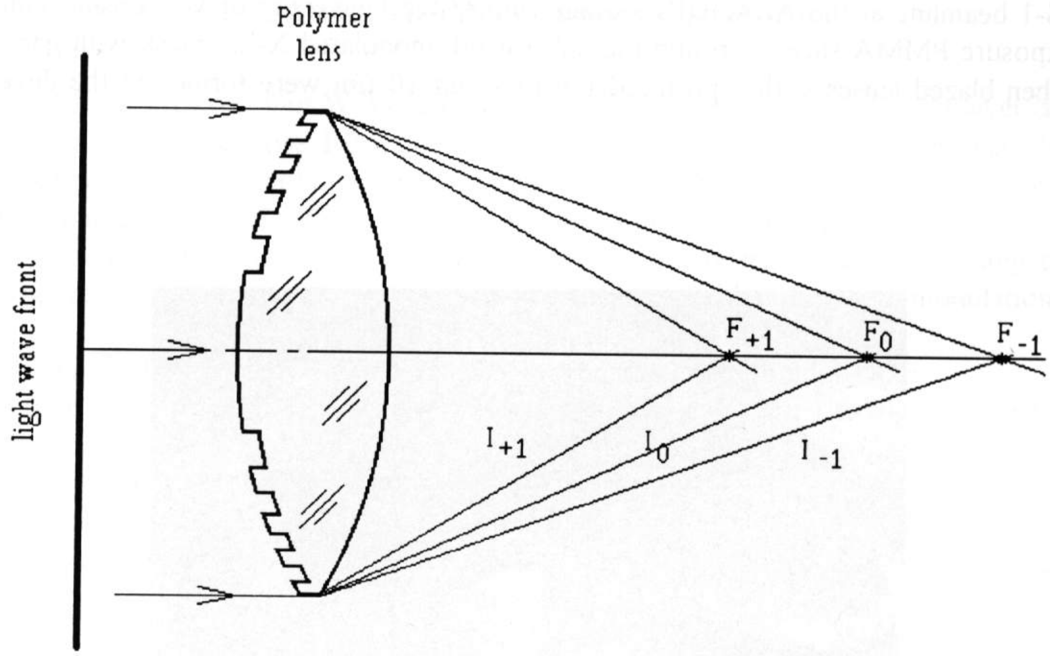

Fig.3. Schematic drawing of the lens focusing in three focal points.

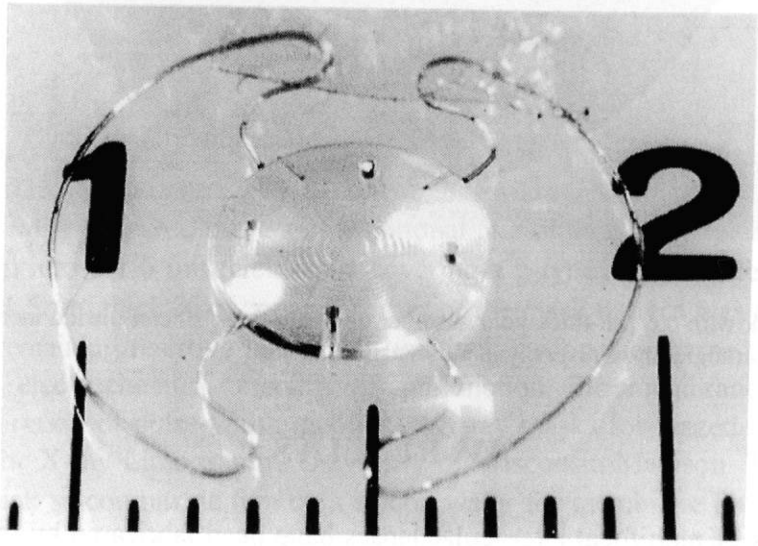

Fig.4. The multifocal interocular lens (focal lengths F_{-1} = 14.1 mm, F_0 = 13.2 mm, F_{+1} = 12.2 mm in the air, diameter ∅ = 5 mm)

Results on fabrication of blazed optical elements with deep-phase profile are demonstrated by an X-ray lithography. Blazed diffraction lenses with 200 mm focal length and 30 mm in diameter, blazed diffraction gratings with 100 μm period and blazed diffraction mirror with 100 mm focal length were produced. Preliminary measurements have demonstrated apochromatic properties for these diffraction mirror and lenses. Diffraction efficiency for lenses is measured for white light. It is higher than 80% for central part of lenses (inside a 10 mm diameter), it is about 60% for 20 mm diameter and about 35 - 40% for total lens area (for 30 mm diameter). The diffraction lens replicated in PMMA sheet (focal length F = - 200 mm, diameter ∅ = 30 mm) with blazed profile of 10 μm depth is shown in Fig.5. Focusing properties of lenses for monochromatic light were studied. Location of the diffractive focuses of different orders and intensity distribution near optical axis were measured. Some of these results are plotted in Fig.6; 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. Focuses locations of different orders, calculated with equation for the focuses of a multiorder diffraction lens, are shown by solid lines. Experimental values are represented by filled dots. In the visible region the lens works for 9 - 14 diffractive orders. First samples of lenses give a rather high level of a diffuse light. It is connected with a roughness of the resist surface after development process.

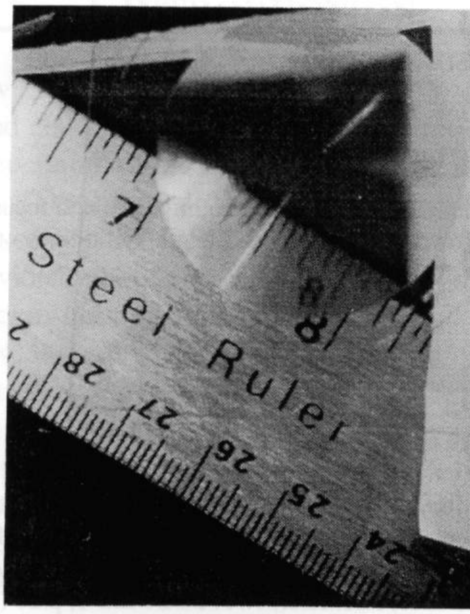

Fig.5. Diffraction lens replicated in PMMA sheet (focal length F = - 200 mm, diameter ∅ = 30 mm) with blazed profile of 10 μm depth.

V. CONCLUSION

The performed experiments demonstrate a possibility to form the diffraction kinoform structures on a spherical surface of the refractive lenses with the use of X-ray lithography technique. Two and three focuses of the fabricated hybrid polymer lenses were observed and the distributions of light intensities at the focal points are in a good agreement with the calculated values.

The verification of capability to make blazed optical diffraction elements with a deep phase relief was done using an X-ray lithography method. A blazed diffraction optical elements with depth of phase profile of about 10 μm were fabricated and its characteristics was measured.

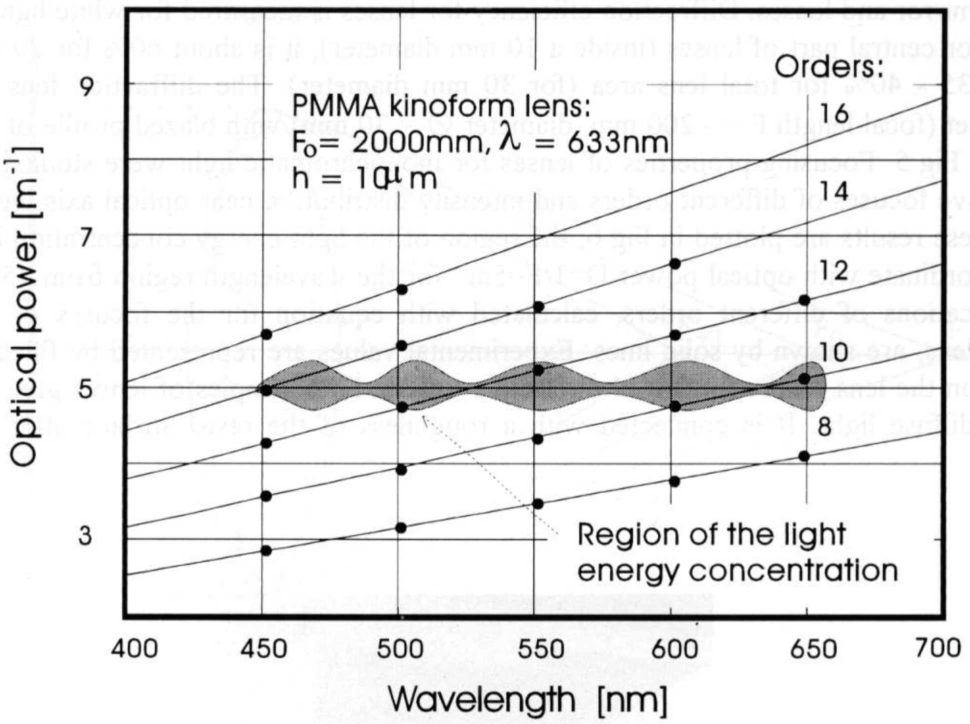

Fig.6. Location of the light energy concentration region (highlighted) and focus locations of different orders in the dependence between an optical power (1/F) and a wavelength. Solid lines - theory, filled dots - experiment.

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