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High-resolution microobjective lens with kinoform corrector*

G. A. LENKOVA, E. G. CHURIN

Institute of Automation and Electrometry, Siberian Branch of USSR Academy of Sciences, 630090, Novosibirsk, USSR.

The hybrid microobjective lens with a kinoform corrector has been developed and fabricated. The kinoform corrector was made by the photorastering technology. The numerical apertures of the microobjective are 0.6 and 0.7; the focal lengths are 9.1 and 5.9 mm. The microobjective can find its applications in various laser interferometers to collimate radiation of diode lasers and for data recording and read-out optical and magnetooptical disks.

1. Introduction

Practical realization of one-element diffraction microobjective lens with high (0.6–0,7) numerical aperture and low light losses is limited by technological possibilities of the photolitographic technique. This is due to the fact that the minimum period of the zones ensuring the diffraction angle required for such an aperture is 1 μm. Besides, to obtain sufficiently high diffraction efficiency (DE) within each zone, a sawtooth (kinoform) profile or a close to it in shape and depth stepped phase should be formed. If one takes into account that the matching accuracy and the edge sharpness that can be achieved in photolitographic process are at best as high as 0.1–0.2 μm, it is clear that the zone period and the shape of the phase profile for outer zones will be distorted during manufacturing (particularly with phase quantization) and due to DE and the resolution of optical elements will considerably decrease.

2. Construction of hybrid element

To increase DE and resolution, a hybrid construction of the microobjective lens including a power lens and a kinoform optical element (KOE) acting as a corrector were chosen. The lens material was TF–10 glass having a high refractive index ($n = 1.784$ for $\lambda = 0.83$ μm).

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The hybrid element was developed and made in two versions (hereafter referred to as 1 and 2). The numerical apertures of the optical element are 0.603 and 0.7, respectively; the light diameters are 11 and 8.2 mm; the focal lengths are 9.1 and 5.9 mm, the diameters of kinoform corrector are 8.5 and 5.3 mm, the minimum sizes of the corrector zones are 13 and 7 μm, and the maximum (calculated) wave spherical aberrations are $\lambda/80$ and $\lambda/14$ (0.0125λ and 0.071λ).

Schematic representation of the hybrid element is given in Fig. 1.

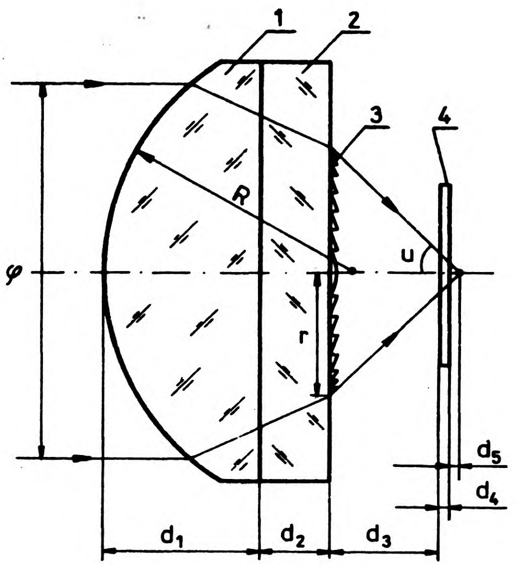

Fig. 1. Construction of hybrid element. 1 – power lens, 2 – substrate, 3 – corrector, 4 – protecting glass of the laser diode, d_1–d_5 – thicknesses of constituting elements and gaps

The power lens is plano-convex in shape. The substrate having kinoform correctors is attached to plane surface of the lens. The construction of the hybrid element was calculated assuming that the convex side of the lens faces a parallel light beam. In this case the lens has minimum spherical aberrations. If the hybrid element is used for beam collimation of the laser diode, the corrector will be on the lens side facing the laser and the lens will be simultaneously a protection for the corrector structure from external effects.

Plano-convex lens is known to possess negative longitudinal aberrations. Hence, for the complete realization of the lens power, the focus of the last beams was chosen as a focal length of the hybrid element. In this case the frequency of the corrector structure is not optimal, but the zone width is sufficiently large. Of course, the focus can be chosen to be a point of intersection on the axes of beams passing through the region of maximum steepness of the corrector phase function, and thus the minimum frequency of the structure would be reduced. But in this case the sign of the optical power of the corrector when passing this region will change, which complicates the programme of photomask recording. Besides, to preserve the aperture magnitude it would be necessary to increase either the lens diameter or the curvature of its surface.

Spherical aberration of the power lens leads to the intersection of beams outside the optical axis. Hence, the question arises, whether the points of intersection will coincide with the corrector plane. To clarify this problem, the paths of several equidistant beams were calculated. It was found that after refraction on the spherical surface the beams do not intersect till their emerging out of the lens, i.e., till their entering the corrector even with the maximum lens size when its radius is equal to that of curvature (Fig. 2). Thus each point of the corrector (lettered AD in Fig. 2) is passed by only one beam.

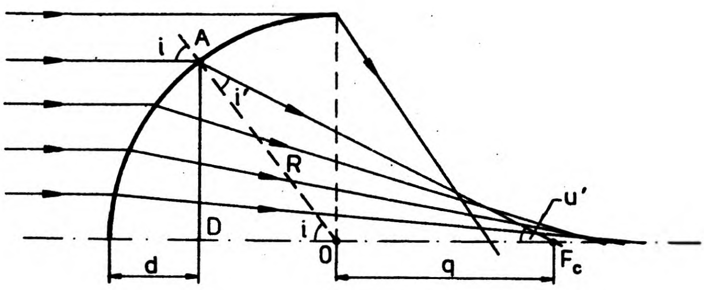

Fig. 2. Each point of the corrector (lettered AD) is passed by only one beam

3. Calculation of diffraction structure and aberrations

Diffraction structure is calculated according to the superposition principle [1], [2], i.e., the phase delay function is represented as a phase difference of two waves. One is a reference wave that is incident to the corrector surface and the other is an objective wave that must be diffracted. A derivation of this function $f' = df/dr$ with respect to the radius r is represented as a difference of the product of the direction cosines $\alpha(r)$ and $\beta(r)$ for the incident and diffracted (or direct and reverse) beams by the refractive indices of materials n_1 and n_2, respectively.

For our case, starting from the superposition principle, we have

$$df/dr = n_2\beta(r) - n_1\alpha(r). \tag{1}$$

Upon substituting the terms of the right-hand side of (1) as expansions into the series:

$$n_1\alpha(r) = \sum_{i=1}^{5} A_i r^{2i-1}, \quad n_2\beta(r) = \sum_{i=1}^{5} B_i r^{2i-1}, \tag{2}$$

we obtain

$$\frac{df}{dr} = \sum_{i=1}^{5} (B_i - A_i) r^{2i-1} = \sum_{i=1}^{5} C_i r^{2i-1}. \tag{3}$$

To find coefficients A_i and B_i and hence C_i, a standard computer program enabling calculation of axisymmetrical systems was used. For several surface points of the kinoform corrector values of the direction cosines for the paths of direct (incident) and reverse (diffracted) rays were calculated. In this case, it is not necessary for the entering points of direct and reverse rays to coincide as assumed in [3], since similarly as in interpolation of a smooth function it suffices that these points are close to each other. For our case it is necessary to solve two systems of five linear equations:

$$\sum_{i=1}^{5} A_i r_k^{2i-1} = \alpha(r_k)n_1, \quad (k = 1, 2, 3, 4, 5), \tag{4}$$

$$\sum_{i=1}^{5} B_i r_j^{2i-1} = \beta(r_j)n_2, \quad (j = 1, 2, 3, 4, 5) \tag{5}$$

where r_k and r_j are the coordinates of the points for which the direction cosines of direct and reverse beams $\alpha(r_k)$ and $\beta(r_j)$ were predetermined.

Upon integrating (3), we obtain

$$f(r) = \int \frac{df}{dr}\, dr = \sum_{i=1}^{5} (C_i r^{2i}/2i) + f_0 \tag{6}$$

where f_0 is the arbitrary constant that does not affect the diffraction corrector function and whose values can easily be varied to calculate radii r for the kinoform zones from the formula $f(r_k) - k\lambda$.

Upon calculating the phase kinoform function, an aberration analysis was carried out that permitted calculation of the residual spherical aberrations of lenses. The plotted functions of the phase delay $f(r)$ and the derivative $f' = df/dr$ for the correctors

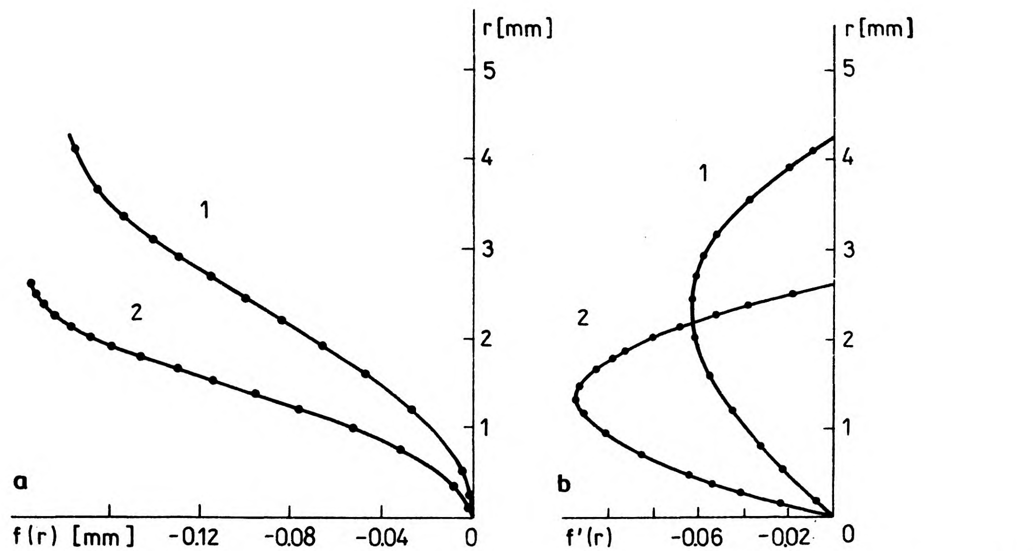

Fig. 3. Phase delay $f(r)$ (a) and the derivative $f' = df/dr$ (b) for the correctors to elements 1 and 2

to elements 1 and 2 are given in Fig. 3**a**, **b**. Plotted transverse and wave aberrations for the hybrid elements with the same correctors are represented in Fig. 4**a**, **b**.

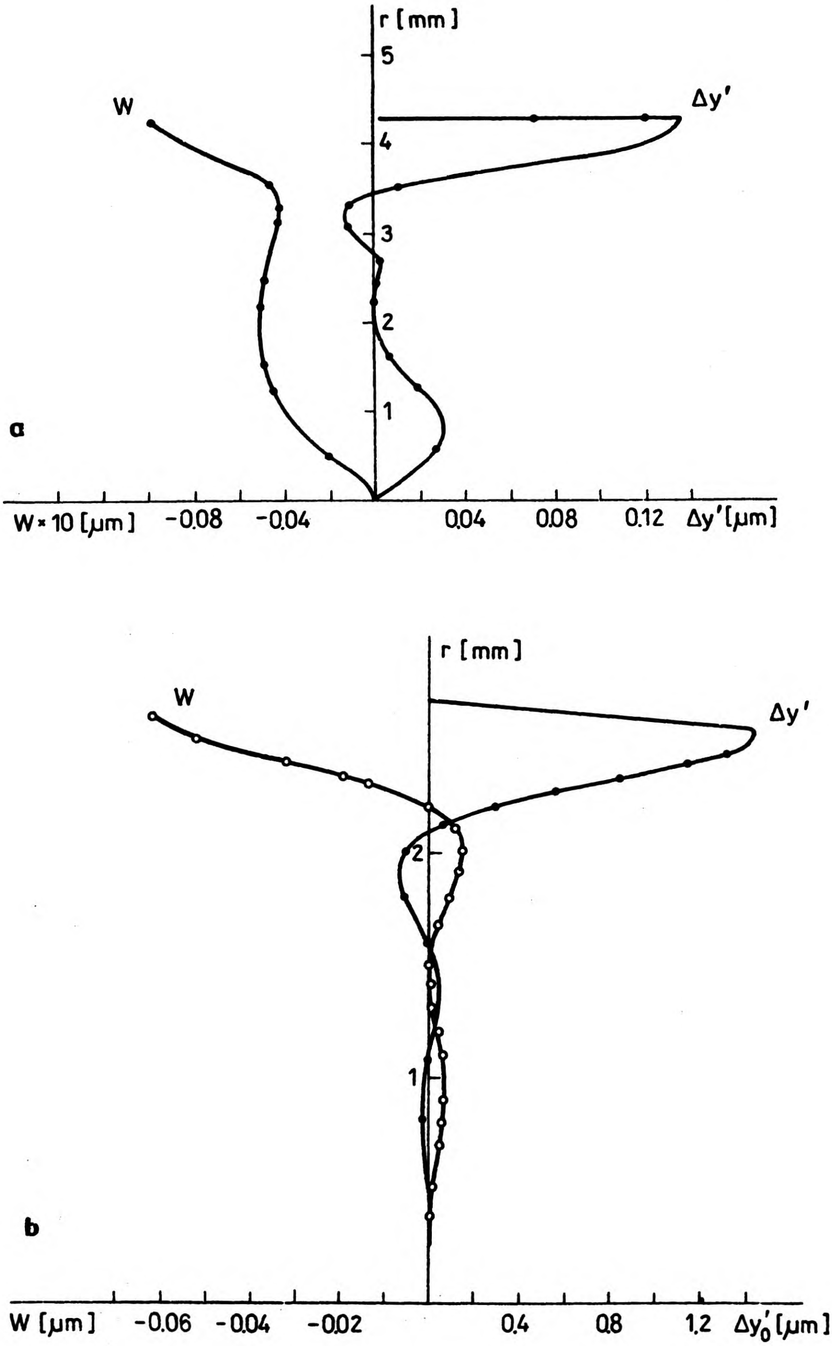

Fig. 4. Transverse ($\Delta y'$) and wave aberrations W for the hybrid elements 1 (**a**) and 2 (**b**)

4. Fabrication of hybrid element and experimental results

Phase sawtoothed microrelief of the corrector was produced using one rastered chromium photomask and a projecting optical system acting as a space-frequency filter [4]. Rastering performs discretization for the initial continuous-tone transmission function of the photomask. The projecting optical system reconstructs intensity distribution in the plane of recording material (photoresist) corresponding to the required phase relief. After exposure with tenfold reduction and development a relief in the photoresist layer is formed. Then through the ion etching this relief is transferred at a given scale to the substrate.

As it was shown [5], in hybrid elements the DE value exerts a considerable effect on the point spread function (PSF), since all diffraction orders are localized in the focal plane of the element. DE value must not be below 85%. In our case photoresist properties do not permit obtaining the necessary relief depths, hence the corrector efficiency was as high as 70% for $\lambda = 0.83$ µm. PSF for hybrid element N1 is illustrated in Fig. 5. As seen, the intensity of the first lateral maximum is 3.3 % of

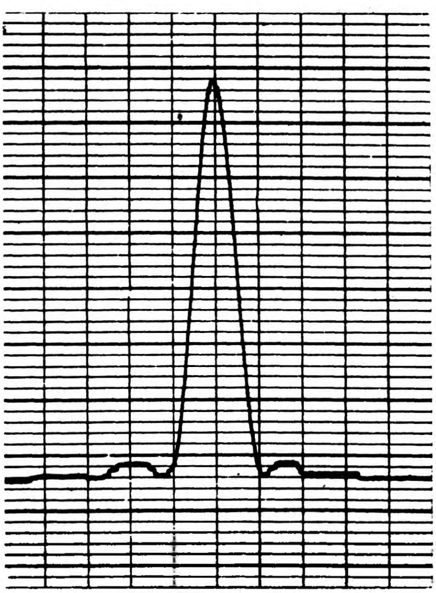

Fig. 5. Point spread function for hybrid element 1

the intensity at the center, which is higher than its theoretical value (1.75%) by a factor of about 1.5%. The measured diameter or diameter of the first dark ring of the focused spot (2.3 µm) was more than its calculated diffraction limited value (1.67 µm). In accordance with the results of the present study [5], it can be attributed to the insufficiently high value of DE. To increase DE, the technology of kinoform corrector fabrication should be further improved.

5. Conclusion

The proposed construction for a high-aperture microobjective lens can find its application in various laser interferometers to collimate radiation of diode lasers and also for data recording and read-out optical and magnetooptical disks.

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Микрообъектив большой разрешающей способности с корректором киноформы

Разработан и выполнен гибридный микрообъектив с корректором киноформы. Корректор киноформы выполнен фотосканирующей технологией. Численная апертура микрообъектива составляла 0,6 и 0,7, фокусное расстояние – 9,1 и 5,9 мм. Микрообъектив может найти применение во многих лазерных интерферометрах для коллимации изменения лазерного диода, регистрации данных, а также в оптических и магнитных отчетных дисках.

Перевел Станислав Ганцаж