LASER APPLICATIONS AND OTHER TOPICS IN QUANTUM ELECTRONICS

PACS numbers: 42.68.Wt; 42.79.Bh
DOI: 10.1070/QE2004v034n03ABEH002626

Controllable objective with deformable mirrors

V.V. Agafonov, A.G. Safronov

Abstract. **A new optical device – an objective with deformable mirrors and parameters controlled in the dynamic regime is proposed. The computer simulation of the objective is performed. The dependences of some parameters of the objective on the control voltage are determined. The simulation showed that the ranges of control of the rear focal segment and the focal distance for the objective with the focal distance 602 mm were 1057 and 340 mm, respectively, which is substantially greater than in the control of an equivalent deformable mirror.**

Keywords: *deformable mirrors, controllable objectives, focal-spot size and position control.*

1. Introduction

Adaptive mirrors [1 – 3] have become firmly established in modern optics. They are used to compensate for dynamic aberrations in various optical schemes, for example, in telescopes [4], which makes it possible to obtain nearly diffraction quality images. These mirrors can be also used to control various parameters, for example, the laser-beam waist in a technological laser system [5]. They can be employed as well as the end or deflecting mirrors in a laser resonator for *Q*-switching, control of the output power and optimisation of the laser parameters [6].

The parameters of deformable mirrors are varied during control within a small range, which is often insufficient. There exist many problems that can be solved only using greater ranges, for example, the problem of controlling parameters of an optical beam focused on a remote target of a complicated spatial shape [7]. Modern deformable mirrors can be employed in new optoelectronic devices, in particular, controllable objectives [8]. These devices are intended to improve the efficiency of control compared to deformable mirrors used outside an objective. They can be used instead of deformable mirrors, increasing the possibilities of the optical system. During control, the parameters of the objective itself and of the optical beam will be varied.

V.V. Agafonov, A.G. Safronov Moscow Power Institute (Technical University), Krasnokazarmennaya ul. 14, 111250 Moscow, Russia; e-mail: sag.mac@g23.relcom.ru

Received 12 November 2002; revision received 25 June 2003
Kvantovaya Elektronika **34** (3) 272 – 276 (2004)
Translated by M.N. Sapozhnikov

A controllable catadioptric objective with one deformable mirror was proposed in Ref. [9]. In this paper, we consider a similar objective with both deformable mirrors.

2. Construction of a controllable objective

A controllable objective – in our case, a controllable catadioptric inverted teleobjective consists of two deformable mirrors (*1*, *2*) and optical lens (*3*) (Fig. 1). Lens (*3*) located in the central hole of contrareflector (*1*) allows the optimisation of the objective parameters. The computer simulation of the objective was performed using the parameters of cooled single-channel deformable mirrors from [2]. The controllable spherical deformations of these mirrors allow us to change the parameters of the objective (focal distance, rear focal segment, focal spot size, etc.) and the optical beam (for example, its divergence) in real time.

The sensitivity (the ratio of the mirror sag to the voltage producing this deformation) of mirrors used in calculations corresponds to the sensitivity of cooled bimorph mirrors [2, 10]. The sensitivity of bimorph mirrors depends on their light diameter. The initial sensitivity of a deformable mirror with a light diameter of 42 mm was taken to be 47 μm kV^{-1}. The sensitivity for a mirror with a different light diameter was calculated from the expression

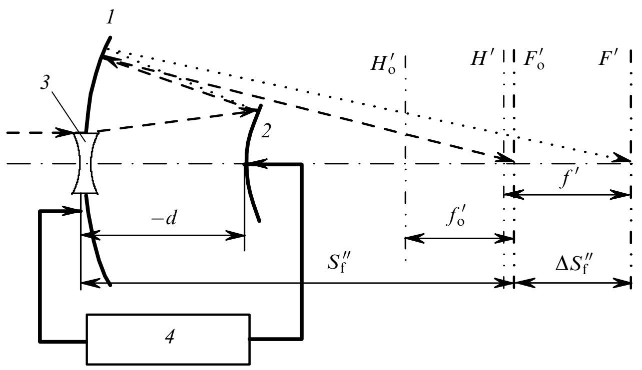

Figure 1. Controllable inverted catadioptric teleobjective (dashed and dotted straight lines show the propagation of the aperture beam, thick arrows denote the control of the curvature of deformable mirrors with the help of the control voltage *U*: (*1*) contrareflector (secondary mirror); (*2*) reflector (primary mirror); (*3*) lens; (*4*) control system; H'_o and F'_o are the rear principal and focal planes, respectively, for $U = 0$; H' and F' are the rear principal and focal planes for $U \neq 0$; S''_f is the reat focal segment; $\Delta S''_f$ is the shift of the rear principal plane; f'_o is the focal length at $U = 0$; f' is the focal length at $U \neq 0$; *d* is the mirror separation.

$$K_2 = K_1(D_2/D_1)^2, \tag{1}$$

where K_1 is the initial sensitivity of a mirror with the light diameter D_1 and K_2 is the sensitivity of a mirror with the light diameter D_2.

We calculated the controllable objective with parameters listed below. A similar objective, but with one deformable mirror, was proposed for the automatic system for correction of laser beam parameters [9].

Parameters of the controllable objective

Focal length f'_o/mm	602
Rear focal segment S''_f/mm	1685.6
Aperture ratio O	0.03
Mirror separation d/mm	−360
Lens focal length f'_{lin}/mm	−400
Lens light diameter D_0/mm	18
Initial reflector surface	flat
Reflector light diameter D_1/mm	34.2
Reflector sensitivity K_1/μm kV^{-1}	31.2
Contrareflector initial radius of curvature R_2/mm	1345.8
Contrareflector light diameter D_2/mm	50.4
Contrareflector sensitivity K_2/μm kV^{-1}	67.7

3. Scheme for calculating a controllable objective and the derivation of basic relations

To derive expressions for calculating the basic parameters of the objective (the focal length and rear focal segment), we write out the initial relations. The dependence of the radius of curvature of a single-channel bimorph mirror on the control voltage is described by the expressions

$$R = \frac{(D/2)^2 + w^2}{2w}, \tag{2}$$

$$w = w_0 + KU, \tag{3}$$

where D is the light diameter of the bimorph mirror; w is the sag of the biomorph mirror; w_0 is the sag of the bimorph mirror in the absence of the control voltage; K is the bimorph mirror sensitivity; and U is the control voltage.

Figure 2 shows the propagation of the aperture beam in the objective. Taking into account the sign rule in optics [11], we can write: $R_1 > 0$ (for $U > 0$, the mirror is convex), R_1 (for $U > 0$, the mirror is concave), $R_2 > 0$, $d < 0$, $S''_f > 0$, $h_0 > 0$, $h_1 > 0$, $h_2 > 0$, $f'_{lin} < 0$, $f'_o > 0$, $\alpha_1 < 0$, $\alpha_2 > 0$, $\varphi > 0$, $\gamma_1 > 0$, $\gamma_2 > 0$, $\varepsilon > 0$; the entrance pupil diameter $D_0 = 2h_0$, and the reflector diameter $D_1 = 2h_1$. From Fig. 2, we can find the following relations:

$$\sin\gamma_1 = \frac{h_1}{R_1}, \tag{4}$$

$$\sin\gamma_2 = \frac{h_2}{R_2}, \tag{5}$$

$$h_2 = h_1 - d\tan(2\gamma_1 - \alpha_1), \tag{6}$$

$$h_1 = h_0\left(1 - \frac{d}{f_{lin}}\right), \tag{7}$$

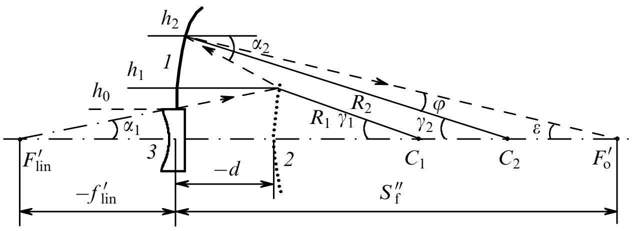

Figure 2. Scheme for the calculation of a catadioptric objective (the dashed straight line shows the propagation of the aperture beam): (*1*) contrareflector; (*2*) reflector; (*3*) lens; h_0 is the height of incidence of the aperture beam on the entrance pupil; h_1 is the height of incidence of the aperture beam on the reflector; h_2 is the height of incidence of the aperture beam on the contrareflector; C_1 the centre of curvature of the reflector; C_2 is the centre of curvature of the contrareflector; R_1 is the radius of curvature of the reflector; R_2 is the radius of curvature of the contrareflector; d is the mirror separation; f'_{lin} is the focal length of the lens; S''_f is the reat focal segment of the objective; F'_{lin} is the rear focal plane of the lens; F'_o is the rear focal plane of the objective.

$$\varphi = \alpha_2 - \gamma_2 = 2\gamma_1 - \alpha_1 - \gamma_2, \tag{8}$$

$$\varepsilon = \gamma_2 - \varphi = 2(\gamma_2 - \gamma_1) + \alpha_1. \tag{9}$$

By substituting (4)–(7) into (9), we obtain

$$\varepsilon = 2\left\{\arcsin\left[\frac{h_1 - d\tan(2\arcsin(h_1/R_1) - \alpha_1)}{R_2}\right] - \arcsin\left(\frac{h_1}{R_1}\right)\right\} + \alpha_1. \tag{10}$$

By using the paraxial approximation $\sin x \approx \tan x \approx x$, we can simplify expression (10) to obtain

$$\varepsilon = \frac{2h_1\{R_1 - (R_2 + 2d)[1 - (R_1\alpha_1/2h_1)]\}}{R_1R_2}. \tag{11}$$

In the case of the normally incident input optical beam with a plane wavefront, we have

$$\alpha_1 = -\arctan\left(\frac{h_0}{f_{lin}}\right) \approx -\frac{h_0}{f_{lin}}. \tag{12}$$

Therefore, the focal length of the catadioptric objective is

$$f'_o = \frac{h_0}{\tan\varepsilon} \approx \frac{h_0R_1R_2}{2h_1\{R_1 - (R_2 + 2d)[1 - (R_1\alpha_1/2h_1)]\}}. \tag{13}$$

By substituting (7) and (12) into (13), we obtain

$$f'_o = \frac{R_1R_2f_{lin}}{2(R_1 - R_2 - 2d)(f_{lin} - d) - R_1(R_2 + 2d)}. \tag{14}$$

The rear focal segment of the objective is

$$S''_f = \frac{h_2}{\tan\varepsilon}. \tag{15}$$

By substituting (6), (7), (11), and (12) into (15) and making some transformations, we obtain

$$S''_f = \frac{[R_1f_{lin} - 2d(R_1 + f_{lin} - d)]R_2}{2(R_1 - R_2 - 2d)(f_{lin} - d) - R_1(R_2 + 2d)}. \tag{16}$$

Therefore, expressions (14) and (16) together with (2) and (3) give the dependence of the focal length f'_o and the rear focal segment S''_f of the controllable catadioptric objective on the voltage.

4. Graphic representation and discussion of results

We developed the software to simulate controllable objectives, which was used to obtain the results presented below. Consider the dependences of the basic parameters of the controllable objective on the control voltage applied to deformable mirrors. For convenience of the analysis, we compare the objective with an equivalent single-channel deformable mirror with the same focal length, the light diameter equal to the diameter of the entry pupil of the objective, and the sensitivity equal to the initial sensitivity (i.e., 47 μm kV^{-1} for the light diameter 42 mm). Therefore, the equivalent deformable mirror has the following parameters: the focal length is 602 mm, the light diameter is 18 mm, and the sensitivity is 8.6 μm kV^{-1}.

Figure 3 shows the dependence of the displacement of the rear focal plane of the controllable objective on the voltage. This dependence for the objective in the first approximation is quadratic and linear for the mirror. As follows from Fig. 3, the controllable objective has a wider control range of the rear focal segment compared to the equivalent mirror even when only one of the mirrors is controlled (3.6 and 8.4 times greater by controlling the reflector and contrareflector, respectively). When both mirrors of the objective are simultaneously controlled, the control range is substantially greater than that for the mirror (by a factor of 13). By the control range of the rear focal segment is meant the distance along the optical axis between the rear focal planes for controlling voltages −200 and 300 V.

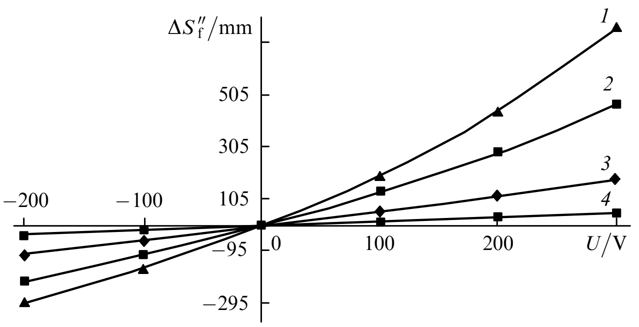

Figure 3. Dependences of the displacement $\Delta S''_f$ of the rear focal plane on the voltage U during the simultaneous control of the reflector and contrareflector (*1*), control of the contrareflector only (*2*), control of the reflector only (*3*), and control of the equivalent deformable mirror (*4*).

Figure 4 shows the dependence of the focal length of the controllable objective and the equivalent deformable mirror on the voltage, which is quadratic for the objective in the first approximation and is linear for the mirror. One can see that, compared to the equivalent mirror, the range of variation in the focal length of the objective is greater when one contrareflector is controlled (by a factor of three) and two mirrors simultaneously (by a factor of 4.3). When the reflector is controlled, the ranges of variation in the focal length of the objective and equivalent mirror virtually coincide (70 and 79.6 mm, respectively). By the control range of the focal length is meant the difference between the focal lengths at the control voltages −200 and 300 V.

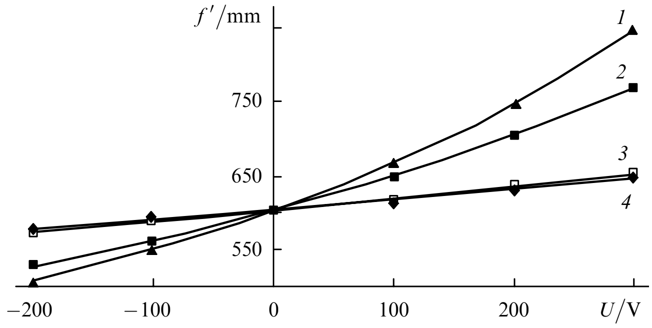

Figure 4. Dependences of the focal length f' on the voltage U during the simultaneous control of the reflector and contrareflector of the objective (*1*), control of the contrareflector only (*2*), control of the equivalent deformable mirror (*3*) or only the objective reflector (*4*).

One can see from Figs 3 and 4 that, when the control voltage is changed from −200 to 300 V, the focal length and rear focal segment of the objective have different control ranges (340 and 1057 mm, respectively). This is explained by the fact that the rear principal and rear focal planes of the objective are displaced differently during control (see Fig. 1). Unlike the objective, the position of the rear principal plane in the deformable mirror does not change during control and, hence, the focal length and rear focal segment change identically. This explains in fact a different increase in the control ranges of the objective parameters compared to the equivalent deformable mirror.

Under certain conditions, namely, if the reflector is located at the focus of the contrareflector, i.e., $d = -R_2/2$, the focal length of the objective does not change when only the reflector is controlled. In this case, the rear principal and focal planes of the controllable objective (see Fig. 1) are displaced in the same direction by the same distance. The rear focal segment will change. For $d \neq -R_2/2$, the focal length of the objective changes during control.

Consider another parameter – the so-called compensated divergence, i.e., the divergence of the input optical beam that can be compensated by the controllable objective. This means that, when the objective mirror or mirrors are deformed, the image plane, in the presence of the divergence of the input optical beam, coincides with the nominal rear focal plane. The nominal focal plane of the objective is the focal plane in the absence of control of mirrors.

Figure 5 shows the dependence of the compensated divergence of the controllable objective and equivalent deformable mirror on the control voltage. The beam divergence compensated with the help of the controllable objective is an order of magnitude greater than the divergence compensated by the equivalent deformable mirror (when both mirrors of the objective are controlled simultaneously, it is greater by a factor of 11).

Figure 6 shows the voltage dependence of the focal spot size taking into account spherical aberration and diffraction (other aberrations are small) for the controllable objective and equivalent deformable mirror. The control range for the focal spot of the objective is four times greater (when the

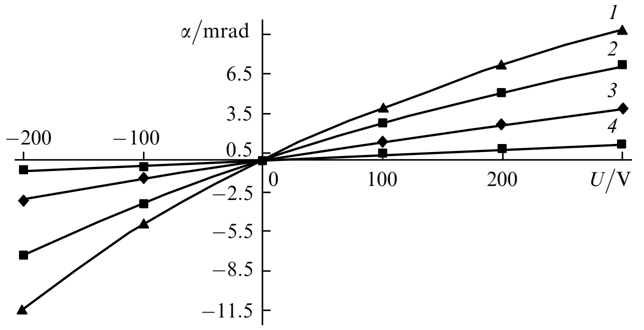

Figure 5. Dependences of the compensated divergence α on the voltage U during the simultaneous control of the reflector and contrareflector of the objective (*1*), control of the contrareflector only (*2*), control of the reflector only (*3*) or the equivalent deformable mirror (*4*).

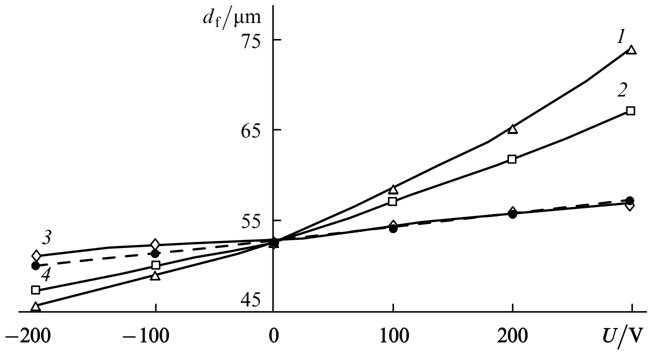

Figure 6. Dependences of the focal-spot size d_f on the voltage U during the simultaneous control of the reflector and contrareflector of the objective (*1*), control of the contrareflector only (*2*), control of the reflector only (*3*) or the equivalent deformable mirror (*4*).

reflector and contrareflector are controlled simultaneously). Diffraction was calculated for a wavelength of 633 nm. The focal spot size was calculated from the expression $d_f = 2(r_d^2 + r_1^2)^{1/2}$, where $r_d = 1.22\lambda/O$ is the diffraction radius of the focal spot; $r_1 = \mathrm{Sum1}/O$ is the focal spot radius calculated from the first Seidel Sum1 (spherical aberration).

Figure 7 shows the voltage dependences of the relative spot size for the controllable objective and equivalent deformable mirror taking into account spherical aberration and diffraction at a wavelength of 633 nm. These dependences are valid for the visible and IR spectral regions because diffraction in these regions dominates over aberrations. The relative spot size is the ratio of spot sizes in the nominal rear focal plane for a given control voltage and for $U = 0$. When the reflector and contrareflector are controlled simultaneously, this ratio achieves 300.

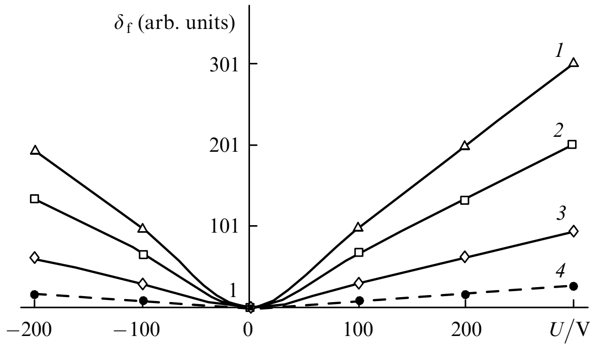

Figure 7. Dependences of the relative focal-spot size δ_f on the voltage U during the simultaneous control of the reflector and contrareflector of the objective (*1*), control of the contrareflector only (*2*), control of the reflector only (*3*) or the equivalent deformable mirror (*4*).

Table 1 presents some results of computer simulations of the controllable objective and equivalent deformable mirror. The focal length of the equivalent mirror coincides with its rear focal segment. One can see from Table 1 that the rear focal segment of the objective changes by 17.4 % (for $U = -200$ V) and 45.3 % (300 V), while the focal length changes by 15.7 % (−200 V) and 40.9 % (−300 V). The focal length and rear focal segment of the equivalent

Table 1. Variations in the main parameters of the objective and equivalent mirror during control.

Control voltage (V)	−200	300	Whole range
Variation in the rear focal segment of the objective during the control of:			
reflector, $\Delta S''_{f1}$/mm	−106.6	179.3	285.9
contrareflector, $\Delta S''_{f2}$/mm	−211.7	462.8	674.5
both reflector and contrareflector, $\Delta S''_{fsum}$/mm	−293.8	762.9	1056.7
Variation in the focal length of the objective during the control of:			
reflector, Δf_1/mm	−26.1	43.9	70.0
contrareflector, Δf_2/mm	−75.6	165.3	240.9
both reflector and contrareflector, Δf_{sum}/mm	−94.4	246.0	340.4
Variation in the focal length and rear focal segment of the equivalent mirror during the control of Δf ($\Delta f = \Delta S''_f$)/mm	−29.4	50.2	79.6
Divergence compensated by the objective during the control of:			
reflector, α_1/mrad	−2.96	3.81	6.77
contrareflector, α_2/mrad	−7.30	7.17	14.47
both reflector and contrareflector, α_{sum}/mrad	−11.25	9.96	21.21
Divergence compensated by the equivalent mirror during control, α/mrad	−0.77	1.15	1.92
Size of the focal spot of the objective during the control of:			
reflector, d_{f1}/μm	51	57	–
contrareflector, d_{f2}/μm	47	67	–
both reflector and contrareflector, d_{fsum}/μm	46	74	–
Size of the focal spot of the equivalent mirror during the control of d_f/μm	50	57	–

deformable mirror change by 4.9 % (for $U = -200$ V) and 8.3 % (300 V), i.e., substantially weaker than for the controllable objective.

5. Conclusions

We have performed computer simulation of a controllable catadioptric objective, which is in essence a new optoelectronic device. The parameters of the objective can be controlled in real time. Our study has shown that available deformable mirrors can be used to construct controllable objectives of different types (Cassegrain, Gregory, Schwarzschild, etc.) [11].

We have found that the controllable objective is much more efficient than the equivalent deformable mirror. In particular, the relative control range of the rear focal segment for the objective with $f_0 = 602$ mm is 63 %, and this range for the focal length is 57 %. The displacement range of the rear focal plane of the objective is greater by a factor of 13 than that for the equivalent mirror, the control range of the focal length is greater by a factor of 4, and the range of the compensated divergence is greater by a factor of 11. In addition, the position of the rear focal plane of the objective can be controlled both by changing its focal length and without it.

Analysis of the results obtained has shown that the dependences of f_o' and $\Delta S_f''$ on the control voltage are quadratic in the first approximation, while similar dependences for the deformable mirror (in the same approximation) are linear. It is obvious that changes in the objective parameters (focal length f_o', mirror separation d, rear focal segment S_f'' , etc.) will result in changes in the control ranges of these parameters.

References

1. Taranenko V.G., Gorokhov Yu.G., Romanyuk N.S. *Zarubezh. Radioelektron.*, (8), 19 (1982).
2. Vinevich B.S., Zharikov V.M., Safronov A.G. *Kvantovaya Elektron.*, **25**, 377 (1998) [*Quantum Electron.*, **28**, 366 (1998)].
3. Vdovin G., Kiyko V. *Opt. Lett.*, **26** (11), 798 (2001).
4. Sychev V.V., Pechenov A.S. *Opt. Zh.*, **68** (8), 93 (2001).
5. Bär K., Freisleben B., Kozlik C., Schmiedl R. *Lasers Eng.*, **4**, 233 (1995).
6. Safronov A.G. RF Patent No. 2217849, 11.10.2000; *Byull. Izobret.*, (33) (2003).
7. Gladush G.G., Drobyazko S.V., Rodionov N.V. Antonova L.I., Senatorov Yu.M. *Kvantovaya Elektron.*, **30**, 1072 (2000) [*Quantum Electron.*, **30**, 1072 (2000)].
8. Agafonov V.V., Safronov A.G. RF Pending Patent No. 2001135271, 27.12.2001.
9. Agafonov V.V., Safronov A.G. *Svetotekhn.*, **4**, 33 (2001).
10. Kokorowski S.A. *J. Opt. Soc. Am.*, **69** (1), 181 (1979).
11. Dubovik A.S., Apenko M.I., Dureiko G.V., et al. *Prikladnaya optika* (Applied Optics) (Moscow: Nedra, 1982).