ADAPTIVE SYSTEM FOR PHASE COMPENSATION OF NONLINEAR DISTORTIONS PRODUCED BY THERMAL SELF-ACTION OF A LIGHT BEAM

V.P. Kandidov, D.P. Krindach, O.A. Mitrofanov, and V.V. Popov

M.V. Lomonosov Moscow State University, Moscow
Received September 10, 1990

The results of a laboratory investigation of adaptive focusing of a laser beam propagating under conditions of wind-induced refraction are presented. A multicriterional algorithm for modal correction of the beam phase is employed. It is shown that the iterational control process is fast and stable.

The development of adaptive optics in many ways determines .progress in improving the efficiency of modern laser systems. Significant success has now been achieved in analysis of methods of adaptive control of the phase of a light beam[1,2,3] and in the development of wavefront correctors. ' At the same time, most experimental investigations in adaptive optics were performed in the 1970s, when the first hopeful results were obtained. The first works on compensation of nonlinear distortions of laser radiation were also performed at that time; see, for example, Refs. 6 and 7. The results of separate experiments on adaptive focusing of a beam in a nonlinear medium were . published later.[8,9]

This paper is devoted to the experimental investigation of adaptive phase compensation of wind-induced refraction of a light beam.

1. Nonlinear distortions of radiation in a moving medium arise in flow-through CO_2 lasers and amplifiers as well as under conditions of propagation in open paths, in the atmosphere. These distortions are manifested primarily as a deflectionof the beam toward the wind and defocusing of the beam in a direction perpendicular to the wind velocity. The wind-reduced refraction can be compensated by controlling the lowest order aberrations of the phase of the light beam. Theoretical analysis shows[10] that when the lowest order aberrations, including the coma, are controlled, the quality criterion of a beam propagating under conditions of wind-induced refraction is equal to 90% of the maximum value attained in the case of control without phase limitations on the beam. As shown in Ref. 11, control of the tilt and curvatures of the wavefront of a beam doubles or triples its focusing criterion. These results provide theoretical justification for the possibility of developing simple and efficient systems for adaptive compensation of wind-induced refraction with the help of modal control of the lowest order phase aberrations. In such systems a comparatively small number (up to ten) control channels is sufficient; such systems are more reliable and their operation is more stable.

The time period during which nonlinear distortions are established under conditions of wind-induced diffraction is determined by the convective time $\tau_v = a_0/V$ (a_0 is the radius of the beam and V is the wind velocity) and is equal to 0.1–1 s. For this reason, wind-induced refraction can be compensated with the help of narrow-band modal phase correctors, which are controlled, for example, by electromechanical drives.

The requirements formulated above are .satisfied by a wavefront corrector (WFC) in the form of an elastic mirror, which is deformed by pistons arranged along the contour of the mirror.[12,13] In this work we employed a mirror with a diameter D = 50–70 mm. The mirror was secured at the center on a metallic elastic substrate. To obtain a reflective surface of optical quality a glass plate was glued on the substrate. In practice, the finishing was performed with a precision of one interference fringe within the working aperture of the mirror, which was equal to 0.5–0.6D. The use of electromechanical drives based on stepping motors provided a wide dynamic range of phase control with displacement of the reflecting surface by up to 300 μm.

The finished mirrors with six equally spaced drives control led the tilts, spherical focusing, and astigmatism of the wavefront of the reflected beam. As a result, the phase of the beam $\varphi(x, y)$ is formed, in the form

$$\varphi(x, y) = 2K \sum_{i=1}^{5} U_i \omega_i(x, y), \qquad (1)$$

where $\omega_i(x, y)$ arethe basis modes of the corrector and U_i is the magnitude of the control for the corresponding mode.

Interference measurements showed that the modes of the mirror $\omega_i(x, y)$ deviate from the Zernike polynomials $Z_i(x, y)$, describing the optical aberrations, by not more than 5, 20, and 15%, respectively, for the tilts, focusing, and astigmatisms.

2. The laboratory investigation of the wind-induced refraction and its compensation is based on the theory of similarity in nonlinear optics. The results of a laboratory experiment on the modal

0235-6880/90/12 1163-7 $02.00

compensation of wind-induced refraction of a light beam are similar to field measurements, if the corresponding similarity criteria are the same.[14]

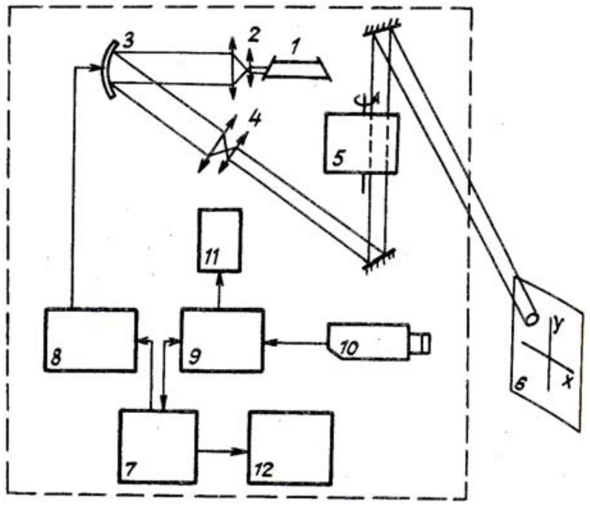

FIG. 1. Block diagram of experimental arrangement: 1) laser; 2, 4) telescopes; 3) controlled mirror; 5) cell; 6) screen in the observation plane; 7) computer; 8) wavefront tilt control unit; 9) recording system; 10) television camera; 11) monitor; 12) information output unit.

Figure 1 shows a block diagram of the adaptive setup developed in accordance with the similarity criteria. The laboratory modeling of the atmospheric path was performed with the help of a vertically positioned cell 5, filled with alcohol. A beam from an argon laser 1 was reflected from the controlled mirror 3 and directed into the cell through the bottom window. After passing through the cell the beam was deflected onto the screen 6 with a mirror and the image from the screen was recorded with a television camera 10 and, after being digitized by the input system 9, it was stored in a computer 7.[15] In the computer the image was processed according to a prescribed algorithm, and commands for the wavefront tilt control unit 8 were formed based on the results of the processing. In this manner the control of the phase of a light beam was closed into a loop.

To simulate the wind the cell was rotated around a vertical axis. By changing the distance between the beam and the axis it was possible to vary the velocity of the "wind," which remained constant along the "path." The similarity criteria were satisfied by prescribing the radius a_0 and the power P_0 of the beam at the point of entry into the cell as well as the absorption coefficient α by adding fuchsine to the alcohol. In this apparatus the length of the cell was equal to $z = 70$ cm, the absorption coefficient $\alpha = 0.01$ cm^{-1}, the radius of the beam $a_0 = 0.7$–1.4 mm, and the flow velocity $V = 0.3$ cm/s. The wavelength of the radiation $\lambda = 0.488$ μm. The beam power P_0 varied from 10 to 50 mW. For these parameters of the apparatus the similarity criteria varied over the following ranges: $z = 0.06$–0.24, $\theta = 4$–18, and $|R_v| = 70$–300.

Quantitative measurements of the beam parameters in the process of control were performed based on the digitized image recorded with the help of the television camera. The values of the peak intensity, the effective width of the beam in directions parallel a_x and perpendicular a_y to the wind velocity, as well as the displacement of the energy center of gravity x_c were calculated on a computer based on the image. An algorithm for controlling the phase was constructed based on these measurements, as will be shown below.

It should be noted that measurements performed with the help of a television camera introduce substantial errors, since its dynamic range makes it impossible to reproduce a distortion-free image of a beam, in whose cross section the intensity varies by more than 1 to 1.5 orders of magnitude. As a result, in a number of cases the peak intensity has an upper limit, and this simultaneously results in overestimation of the effective beam width. For this reason, absolute measurements of the radius .of the beam were performed with the help of a scaled screen (the error did not exceed 10%), and the peak intensity was measured with the help of a power meter of the type SPECTRA-PHYSICS-404 with a 0.5 mm in diameter diaphragm.

3. The adaptive control algorithm, with whose help the control signals are formed, is one of the main factors determining the stability and convergence of the compensation process. The theoretical analysis performed in Ref. 3 shows that the phase conjugation procedure becomes unstable as the parameter of nonlinear refraction R_v increases. In a modal system with a small number of control channels it is preferable to use algorithms based on the gradient of the optimization of some criterion of beam quality.[16] This criterion is usually a scalar quantity, for example, functionals of the focusing, sharpness, etc.[1] However practical implementation of control based on a scalar criterion meets with serious difficulties. First, gradient methods of optimization converge slowly near an extremum and they are not very stable when noise is present in the recording channel. Second, when a scalar criterion is employed all control coordinates become equivalent and interrelated, and this lowers the stability of the optimization process and the speed of operation of the adaptive system. For this reason, in the last few years great efforts have been directed toward searching for new control algorithms.[17,18]

Under conditions of modal control in a basis of the lowest order optical aberrations the efficiency of the operation of the adaptive optical system based on simultaneous analysis of a collection of scalar criteria, which must meet the requirement that the control channels be separated, can be significantly increased.

Dedicated processing of the image of the light beam in the observation plane gives the necessary information for obtaining such a collection of criteria.

A multicriterional, modal control algorithm was employed in the apparatus. The algorithm is based on the construction of functionals $\hat{F}_i\left[I(x, y, z_0)\right]$ of the intensity $I(x, y, z_0)$ in the observation plane z_0 which depend predominantly on the control U_i for the corresponding mode $\omega_i(x, y)$:

$$\hat{F}_1\left[I(x, y, z_0)\right] = f_1(U_1; \mu U_j), \quad \mu \ll 1, \; i \neq j \;, \tag{2}$$

where the parameter μ characterizes the crosstalk.

Let $I(x, y, z_0)$ be the running value of the intensity, and let $I^0(x, y, z_0)$ be the required distribution of the intensity in the plane z_0, when the components of the vector quality criterion **J** are as follows:

$$J_1 = \hat{F}_1\left[I(x, y, z_0)\right] - \hat{F}_1\left[I^0(x, y, z_0)\right]. \tag{3}$$

If the functionals $\hat{F}_i$ depend linearly on the control U_i, then the vector of the control sought U_i^0, for which the values of $\hat{F}_i^0$ are attained is determined by the formula

$$\mathbf{U}^0 = \mathbf{U} - \hat{A}\mathbf{J}, \tag{4}$$

where $\hat{A}$ is the control matrix.

In the case $\mu = 0$ the functionals $\hat{F}_i$ become the conjugate modes $\omega_i(x, y)$ and the matrix $\hat{A}$ is diagonal. The control channels are completely decoupled when the value U_i sought for each component of the control vector is determined only by the corresponding component J_i of the criterion vector.

In practice the crosstalk between the control channels ($\mu \not\equiv 0$) can be caused by different factors. Here the question of the existence of conjugate operators is fundamental; it is related with the particular choice of basis of modal control ω_i.

No less important is the question of the possibility of calculating these functionals in practice. Further, crosstalk can arise owing to the error in the reproduction of the modes by a real phase corrector. Finally, in a nonlinear medium the principle of superposition breaks down, and in the case of control for some channel all intensity functionals change. In this case the elements of the matrix $\hat{A}$ depend on the distribution of the intensity and the process of formation of a prescribed intensity profile $I^0(x, y, z_0)$ becomes iterative. The increment to the control vector ΔU^k at the kth iteration step can be calculated by linearizing the relation (4):

$$\Delta\mathbf{U}^k = \hat{A}\left(I^{k-1}\right)\Delta\mathbf{J}^{k-1}. \tag{5}$$

If, however, these factors are not dominant, i. e., the relative error of the wavefront tilt is small, the control functionals are close to being conjugate ($\mu \ll 1$ in Eq. (2)), the nonlinearity is weak, and linear diffraction processes accompanying beam propagation predominate, then it can be expected that the control channels will be virtually independent of one another and the matrix $\hat{A}$ will be nearly diagonal. As a result, the use of a multicriterional algorithm under real conditions will make it possible to speed up convergence and to improve the stability of the iteration process of adaptive control of the phase of a light beam.

The analysis performed for the case of a linear propagation medium showed that when controlling the phase of a light beam the following functionals can be used as the functionals $\hat{F}_i$, conjugate to the basis modes, in the basis of the lowest order optical aberrations:

$$\begin{gathered}\hat{F}_1[I] = M\{x\} = x_c; \quad \hat{F}_2[I] = M\{y\} = y_c; \\ \hat{F}_{3,4}[I] = M\left\{(x - x_c)^2\right\} \pm M\left\{(y - y_c)^2\right\} = a_x^2 \pm a_y^2; \\ \hat{F}_5[I] = M\left\{(x - x_c)(y - y_c)\right\} = a_{xy},\end{gathered} \tag{6}$$

where

$$M\left\{f(x, y)\right\} = \frac{\int f(x, y) I(x, y, z_0)\, dxdy}{\int I(x, y, z_0)\, dxdy}.$$

and x_c and y_c are coordinates of the shifted energy center of gravity. For the functionals $\hat{F}_i$ ($i = 1, 2$) the. parameter μ is equal to zero, and the functionals $\hat{F}_4$ and $\hat{F}_5$ have a dependence on the focusing control U_3 with parameter $\mu = z_0$. The functional $\hat{F}_3$ also depends on the controls U_4 and U_5. For this reason, to decouple the control channels it is necessary to use successive compensation in the focusing problem. First, by controlling the asigmatisms U_4 and U_5, the moduli of the functionals $\left|\hat{F}_4\right|$ and $\left|\hat{F}_5\right|$ are minimized to a prescribed accuracy. As a result the effect of these aberrations on the magnitude of the functional $\hat{F}_3$, characterizing focusing, decreases. Next, control of focusing is performed. When $\hat{F}_3$ reaches a minimum value, the system, when necessary, once again returns to control of asigmatisms. In this manner, an iterative process of step-by-step control of astigmatisms and focusing is organized; in this process, it is possible to decouple significantly the control channels for second-order aberrations. The above-described process of modal control weakens the algorithmic coupling between the channels, which appears when one or another procedure is used to processing the image and for forming the control signals. Obviously, the coupling between the modes for nonlinear distortions, where the principle of superposition breaks down, cannot be broken by control methods.

We note that since there is no crosstalk between the control channels for first and second order aberrations, in making the corrections simultaneous control of the tilts ω_1 and ω_2 and the astigmatisms ω_4 and ω_5 can be employed, in accordance with Eq. (4).

4. We shall study the compensation of wind-induced refraction with comparatively low beam power P_0 = 25 mW, which corresponds to a nonlinearity parameter R_v = –130. In this case, the characteristic increase in phase, estimated in the fixed-field approximation, is $\varphi \sim R_v z \sim 8$ rad.

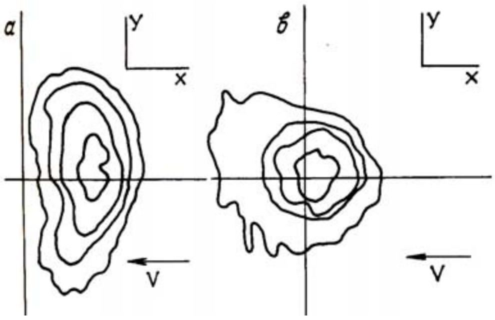

FIG. 2. Image of a light beam in the steady-state' regime of wind-induced refraction: a) without compensation; b) after completion of the adaptive compensation process. The position of intersection of the solid lines corresponds to the position of the energy center of the beam in the absence of nonlinear distortions.

The steady-state regime of wind-induced refraction for given parameters of the radiation is illustrated in Fig. 2. In the absence of control the image of the beam is crescent-shaped: the beam width a_0 in a direction perpendicular to the flow is 2 to 2.5 times larger than the width a in the direction of the flow and the energy center of the beam is displaced toward the wind by a distance equal to the radius of the broadened spot.

After the feedback loop is closed, the astigmatisms, focusing of the beam, and aiming of the beam into a given point are performed in the control system. After the iterative process of adaptive compensation of distortions is completed, the image ofthe beam assumes a nearly axisymmetric form; the center of gravity of the beam lies virtually in the point into which the beam is aimed (Fig. 2b).

The change in the distribution of intensity I in cross sections of the beam is shown in Fig. 3. One can see from the figure that focusing in a plane perpendicular to the flow results in increase of the peak intensity in the observation plane (Fig. 3b). Insignificant additional focusing and deflection of the beam, in order to aim its center of gravity at the point of observation, occur in a plane parallel to the flow (Fig. 3a). Based on the computer data, the divergence of the beam in a direction perpendicular to the wind direction decrease by a factor of 2 and thedivergence along the flow decreased by 30-40%. Based on visual measurements performed with the help of scaled screens the angular divergence of the central maximum of the beam is equal to 1.3–1.5 of the diffraction divergence. The peak intensity was 2.2–2.4 times higher after compensation.

The changes in the components of the criterion vector **J**, the characteristics of the beam a_x, a_y, and x_c, and the magnitudes of the control signals **U** in the process of adaptive compensation are presented in Fig. 4. One can see that in the first two steps (N = 1, 2), after feedback is switched on, the system corrects the astigmatism U_4 and then transfers to focusing control, N = 3 (Figs. 4a and b). After this additional astigmatism correction is performed (N = 4). Once the beam is focused with a given accuracy (N = 5, 6), the system transfers to tilt control U_1 (N = 7). The iterative control process stopped after 8 steps.

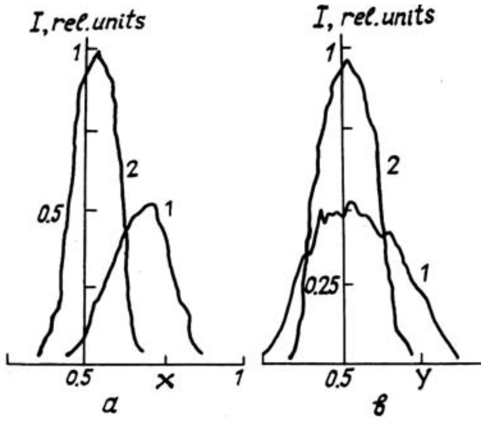

FIG. 3. Distribution of intensity in cross sections of the beam in the steady-state regime of wind-induced refraction: a) along the Ox-axis; b) along the Oy-axis, passing through the energy center of the beam; 1) without compensation, 2) after adaptive focusing.

The change in the energy center of the beam x_c and the effective width of the beam a_x and a_y measured along the Ox and Oy axes In the process of control Is presented in Fig. 4c. One can see how the width a_y decreases and at the same time a_x increases with astigmatism control U_4 at the steps N = 1, 2 and also N = 4. In the case of focusing, performed at the steps N = 3 and N = 5 and 6, both widths a_x and a_y decrease. Tilt control U_1 at the seventh and eighth steps has virtually no effect on the beam dimensions a_x and a_y, and ensures that the beam is aimed at the given point.

Similar investigations were performed for other values of the nonlinearity parameter. Thus for the power P = 50 mW (R_v = –260), after adaptive compensation the angular divergence in a direction perpendicular to the wind velocity decreased by a factor of 2, while in the direction of the flow it decreased by a factor of 1.6. As a result the angular divergence of the beam at the exit from the cell was equal to 1.7–1.9 times the diffraction-limited value. The peak intensity in the beam was approximately 2.6 times higher after control.

5. The results of these investigations show that modal control of the phase of a light beam is effective for compensating nonlinear distortions caused by wind-induced refraction. The experiments demonstrated that the convergence of the multicriterional control algorithm is stable under conditions of

nonlinearity. The iterative process of compensation of nonlinear distortions is completed after 8 to 10 control steps. For duration of one step equal to Is the quasistationary adaptive control based on a multicriterional algorithm makes it possible to track slow wind velocity pulsations, whose characteristic period is equal to ~ 10 s, on atmospheric paths.

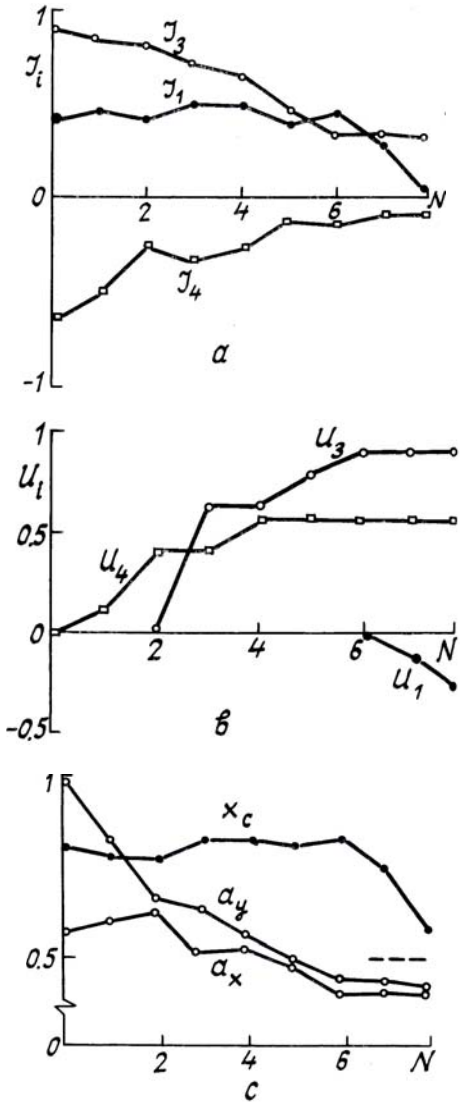

FIG. 4. The behavior of the components of the criterion vector **J** *(a), the control vector* **U** *(b), and the characteristics of the beam (c) in the process of compensation of wind-induced refraction ($R_v \simeq -130$, $\theta \simeq 18$). The broken line corresponds to the coordinate x_c of the energy center in the absence of nonlinear distortions.*

REFERENCES

1. M.A. Vorontsov and V.I. Shmal'gauzen, *Principles of Adaptive Optics* (Nauka, Novosibirsk, 1985).
2. V.P. Lukin, *Atmospheric Adaptive Optics* (Nauka, Novosibirsk, 1986).
3. V.A. Vysloukh, V.P. Kandidov, S.S. Chesnokov, and S.A. Shlenov, Izv. Vyssh. Uchebn. Zaved. SSSR, Ser. Fiz. **28**, No. 11, 30–41 (1985).
4. V.G. Taranenko, Yu.G. Gorokhov, and N.R. Romanyuk, Zarubezhnaya Radioelektronika, No. 8, 19–43 (1982).
5. M.A. Vorontzov, S.A. Gnedoi, A.V. Kudryashov, et al., "*Mirrors based on passive bimorphons elements,*" Preprint No. 29, Scientific Research Center of Laser Technology, Academy of Sciences of the USSR, Shatura (1987).
6. C.A. Primmerman and D.G. Fouche, Appl. Opt. **15**, No. 14, 990–995 (1976).
7. W.B. Bridges and J.E. Pearson, Appl. Phys. Lett. **26**, No. 9, 539–543 (1975).
8. A.V. Ivanov, V.P. Kandidov, D.P. Krindach, and V.V. Popov, in: *Abstracts of Reports at the 5th All-Union Conference on Laser Optics*, State Optical Institute, Leningrad, (1986), pp. 205.
9. A.A. Vasil'ev, M.A. Vorontzov, I.A. Kudryashov, and V.I. Shmal'gauzen, Kvant. Elektron. **14**, 1735–1736 (1987).
10. D.A. Nahrstedt, Appl. Opt. **22**, No. 2, 224–252 (1983).
11. S.S. Chesnokov, Kvant. Elektron. **10**, 1160–1165 (1983).
12. V.P. Kandidov, I.V. Larionova, and V.V. Popov, Atm. Opt. **2**, No. 8, 836 (1989).
13. V.P. Kandidov and V.V. Popov, "*Modal corrector for compensation of the lowest-order optical Aberrations,*" Preprint No. 16, M.V. Lomonosov Moscow State University, Moscow (1989), 5 pp.
14. V.P. Kandidov, D.P. Krindach, V.V. Popov, and S.S. Chesnokov, in: *Propagation of Optical Waves in the Atmosphere and Adaptive Optics,* Tomsk Affiliate of the Siberian Branch of the Academy of Sciences of the USSR, Tomsk (1988), p. 9.
15. O.A. Mitrofanov and V.V. Popov, Prib. Tekhn. Eksp., No. 5, 249 (1989).
16. S.S. Chesnokov, Izvest. Vyssh. Uchebn. Zaved., Ser. Fis. **50**, 796–798 (1986).
17. A.P. Sukhorukov and V.A. Trofimov, Kvant. Elektron. **14**, 2261–2263 (1987).
18. D.A. Bezuglov, Kvant. Elektron. **16**, 1612–1616 (1989).
19. V.P. Kandidov, O.A. Mitrofanov, and V.V. Popov, Kvant. Elektron. **16**, 1548–1550 (1989).