SOME PROBLEMS OF COMPENSATION FOR NONLINEAR DISTORTIONS OF LIGHT BEAMS. FORMATION OF A LIGHT BEAM WAVE FRONT

V.A. Trofimov

M.V. Lomonosov State University, Moscow
Received October 6, 1992

The problem of formation of a light beam wave front with flexible or segmented mirrors is considered. A detailed analysis of the influence of the beam intensity profile as well as of the ratio of an actuator range to a beam radius on the quality of the beam focusing is given. Some feasible approaches to modeling of the focusing procedure when using a segmented mirror are discussed. Certain differences between the results obtained using the present field approximation and those obtained using numerical simulations on inversion of the wave front in the case of four–wave interaction under conditions of strong energy exchange between the waves and their self–action are pointed out.

INTRODUCTION

One of the important problems of compensation for amplitude–phase distortions of optical radiation is the formation of the required wave front surfaces, e.g., using flexible and segmented mirrors, liquid crystals, and the methods of nonlinear optics. Different questions concerned with this problem are discussed in Refs. 1–37. In this paper we give a brief review of our previous studies on the selection of mirror geometry (the number of its degrees of freedom and arrangement of actuators), the possibility of parallel control of different channels of the mirror deformation, the simulation of phase conjugation (PC), and the like.

FLEXIBLE MIRRORS

In this section we discuss the problems of formation of the required surface on a flexible mirror at the expense of disturbances applied to some points (actuators) for focusing the light beam. In so doing two limiting cases must be distinguished for the relation between the radius a_{ac} of action of an individual actuator and the radius a of the beam: (1) $a_{ac} \gg a$ and (2) $a_{ac} \ll a$.

It should be noted that in the linear medium[16] for the small number of actuators and under condition $a_{ac} \gg a$ a high–quality beam can be focused with a flexible mirror when its response function is close to the Gaussian or involves a quadratic segment of deformation disturbance. By arranging the other actuators beyond the region occupied with the light beam or by rigidly fixing the edge of the mirror it is easy to realize a parabolic profile of the mirror. This conclusion is also drawn from formula (5) (Ref. 20) for the optimal quantity θ_1 of deformation of a flexible mirror with the Gaussian response function $\Phi = \exp(-(x^2 + y^2)/a_{ac}^2)$ during the Gaussian beam focusing

$$\theta_1 a_{ac}^2 = (1 + a_{ac}^2)\,\theta , \qquad (1)$$

where θ is the dimensionless parameter specifying the beam focusing ($S = \theta(x^2 + y^2)$ is the wave front; x and y are the transverse coordinates normalized to a) and a_{ac} is the dimensionless parameter equal to the ratio of the effective range of an individual actuator to the beam radius. Hence, for $a_{ac} \gg 1$ the curvature of the parabolic front in the range of the beam propagation coincides with the mirror curvature. For the beam self–action, highly efficient control of such a mirror (as for a perfect corrector) is attained when the inequality $z^2(1 + \alpha) \ll 1$ holds (z and α are the normalized longitudinal coordinate and the nonlinearity parameter, respectively[37]), i.e., basically, for phase distortions. The numerical simulation performed by Kanev and Chesnokov[16] supports these conclusions.

If the effective range of an individual actuator is comparable to or smaller than the beam radius (this is the case that is frequently encountered in the problems of light energy transport[1–3]), then optimization of the actuators arrangement and of their number acquired the greater importance than that for the above–discussed case $a_{ac} \gg 1$. This problem is examined in our papers.[20,21,27,35,36–39] Some of those conclusions are reproduced in this paper.

First of all we consider the efficiency of a profiled beam focusing with a flexible mirror having an actuator at its center and rigidly fixed around its circles.[35] The form of the response function of actuator is Gaussian or bell–shaped

$$\Phi = ch^{-2}(x/a_{ac},\, y/a_{ac}) . \qquad (2)$$

Propagation of the light beam is described by a quasioptical equation

$$\partial A/\partial z + i\,\Delta_\perp A + i\,\alpha\,\varepsilon_{nl} A = 0 \qquad (3)$$

with the boundary condition

$$A\big|_{z=0} = \frac{0.5\exp\left(-2x^m - 2y^m - i\,S(x, y)\right)}{\int\int \exp(-4x^m - 4y^m)\,dx\,dy} ,$$

$$S = \theta_1\,\Phi, \qquad (4)$$

where m is the parameter equal to 2, 4, 6, 8, and 10 which indicates that the beam profile is close to uniform distribution. In the numerical experiments on focusing in a medium with the Kerr nonlinearity $\varepsilon_{nl} = \alpha|A|^2$ and in a moving medium with a thermal mechanism of nonlinearity $\varepsilon_{nl} = \alpha\int|A|^2\,d\xi$ the parameter $|\alpha|$ was equal to 20, the radius of the receiving aperture $R_a = 0.25$ (the aperture function within R_a equals 1), and the receiver was placed in the cross section $z = 0.1$ ($0.2\ \kappa a^2$). The quality of compensation for the beam defocusing was estimated based on a portion of its power j_r received by the aperture. Figures 1 and 2 depict the calculational results obtained for the mirrors with the Gaussian and bell–shaped functions as dependences of the value of j_r on the relation between the effective range of the actuator and the initial radius of the beam.

Let us first consider the beam focusing in a linear medium. It is easy to draw some conclusions by analyzing Fig. 1. First, there is an optimal value $(a_{ac})_{opt}$. In the situation under study it equals 0.72 (for a Gaussian beam) and 0.8 (for a hyper–Gaussian beam with $m = 6$ and 10). It should be noted that when a_{ac} exceeds $(a_{ac})_{opt}$ the quality of focusing decreases slower than when a_{ac} decreases. Second, there is an optimal profile of the beam in the class of distributions (4). Thus in going from a Gaussian to hyper–Gaussian profile of the beam with $m = 6$ and depending on a_{ac}, it is possible to increase a power concentration at the receiver by a factor of 1.3–1.5. Third, near the optimal focusing the dependence of the received power j_r on the mirror deformation for a hyper–Gaussian beam is smoother than that for a Gaussian beam. The detuning of focusing from $(\theta_1)_{opt}$ for the quantity 0.3–0.4 gives a few percent decrease in power concentration. On the one hand, this makes the requirements for a focusing accuracy weaker and, on the other hand, can slow down the convergence of the iteration process. It should be noted that in the considered case the beam focusing with a flexible mirror with a single actuator positioned at its center increases the power concentration at the receiver by a factor of 1.4–2.2 compared with the value obtained using a collimated Gaussian beam. The beam profiling makes it possible to increase further the power concentration at the receiver by a factor of 1.7–2.9. However, the value of j_r under the wave–front multidimensional control exceeds essentially j_r at optimal θ_1. Thus, even for $(a_{ac})_{opt}$ the power concentration at the receiver obtained due to the beam focusing is 2.1 times lower than j_r being reached under the multidimensional control.

The foregoing conclusions are also valid for beam focusing in the Kerr medium. However, the nonlinearity of propagation produces some differences in the j_r dependence on a_{ac}. In particular, there occurs a nonmonotonic dependence of the received power on a_{ac}. The quality of focusing of the Gaussian beams decreases approximately by a factor of 1.2–1.4. As for the hyper–Gaussian beams, the value of j_r differs slightly from j_r being reached in the linear medium using a mirror with the Gaussian response, and when $m = 10$ in the Kerr medium the power concentration becomes even higher. The reason is that the beam first propagates through a part of the path with a uniform profile[39,40] and then it is transformed to a Gaussian one. Due to this fact, first, the nonlinear distortion of the wave–front decreases and, second, it apparently has no time to be transformed into an amplitude one. Since the mirror response profile and the beam phase distortion are similar the quality of compensation becomes higher. Therefore it is appropriate to transfer to the profiled beams: along the certain paths the nonlinearity of beam propagation does not result worsening the quality of focusing. The path can be prolonged due to the control over the beam radius. It should be noted that a multidimensional control of the beam phase leads to the four–fold increase of the power at the receiver.

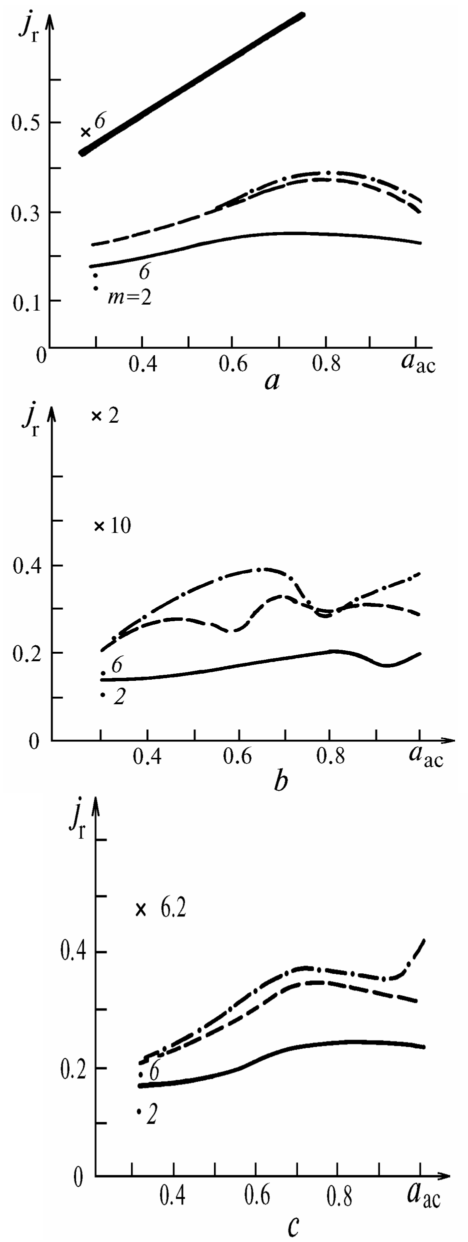

FIG. 1. Power at the receiver vs the ratio of the effective range of an individual actuator to the Gaussian (solid curve), hyper–Gaussian with $m = 6$ (dashed curve) and $m = 10$ (dot–dashed curve) beams during focusing with a mirror with a Gaussian function response in linear (a), Kerr (b), and moving with a thermal mechanism of nonlinearity (c) media. Dots stand for the values of j_r corresponding to the beam collimated upon entering the medium and crosses symbolize the values j_r reached under multidimensional control without limiting the number of the mirror degrees of freedom. Figures denote the parameter m.

When the beam is focused in a moving medium (see Fig. 1*c*) the power concentration at the receiver increases with increase of a_{ac} (only for a hyper–Gaussian beam with $m = 6$ the quantity j_r decreases when $a_{ac} \geq 0.75$).

The transition to profiled beams is much more efficient than in the previous cases and the result is a 1.3–1.8 fold increase of the power. It is worth noting that the multidimensional control leads to a two–fold increase of the received power. In addition, the same value of j_r is reached for a Gaussian beam and a hyper–Gaussian beam with $m = 6$. This is accounted for by the fact that during the severe focusing of optical radiation strong self–deflection of a light beam occurs which is caused by transverse motion of the medium and its center goes beyond the receiving aperture. An important point is that the dependence of the received power on the relation between the beam radius and the effective range of the actuator is determined by the size of the receiving aperture. As an illustration of this statement Fig. 1*a* depicts a plot of j_r vs a_{ac} for $R_a = 0.5$ (heavy curve at the top). The figure shows a monotonic increase of power concentration at the receiver with increase of a_{ac}.

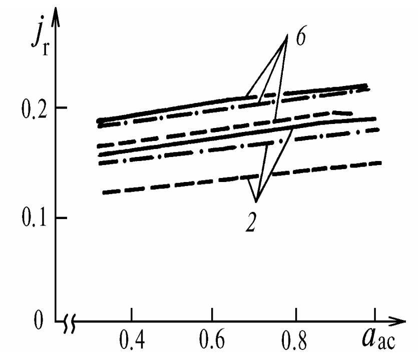

FIG. 2. Dependences are the same as in Fig. 1, but when the beam focusing is performing by a mirror with a bell–shaped response function in linear (solid curves) and moving with a thermal mechanism of nonlinearity (dot–dashed curve) media. Figures near the curves denote the values of the parameter m.

A comparison of the values of j_r during the beam focusing by means of the mirror with the Gaussian and bell–shaped response function (Fig. 2) indicates that in the latter case the power concentration at the receiver is 1.12–2 times lower. However for small a_{ac} the difference in the focusing efficiencies decreases and the transition to profiled beams (as is noted above) enables one to increase j_r.

Thus to improve the quality of focusing with small a_{ac} it is necessary to increase the number of actuators. In this case, the problem of their arrangement arises. To achieve high quality of the appropriate surface of the mirror we must increase the number of its degrees of freedom while to increase the high–speed of the system, which also affects the quality of focusing under the dynamic control, it is necessary to minimize the number of actuators.

The control depends also on how much the ranges of individual actuators are overlapped. If several actuators act on each part of the mirror, then the overlapping of the ranges of actuators will be strong and the breakdown of the iteration convergence in one channel unavoidably leads to the same effect in the other channels. In the case of weak overlapping, it is possible to organize the parallel control of all the actuators. Therefore there exists a strategy for optimal arrangement of actuators.

As is known, in a linear medium the actuators are arranged so that their groups can form the mirror surface described with Zernike polynomials. This strategy can be inefficient for nonlinear propagation.

Let us analyze some ways for arranging the actuators.[20] Figure 3 shows the fragments of mirrors. For the variant shown in Fig. 3*a* a total number of actuators in a square whose side is equal to the beamwidth is $N_{ac} = 4a_{r-d}(a_{r-d} + 1) + 1$, and there is approximately four–fold overlapping of actuators. Here a_{r-d} is the ratio of the beam radius a to the distance at which the actuators are positioned from each other. When they are arranged around the circles of radii κa_{r-d} ($\kappa = 0, 1,...,$) at a distance of a_{r-d} from each other their total number is $N_{ac} = 3a_{r-d}(a_{r-d} + 1) + 1$. About three actuators act on each element of the mirror surface. It is possible to decrease N_{ac} if the actuators will be positioned at a distance of $2a_{r-d}$ between the centers and one more actuator – at the center of each square $2a_{r-d}$ on a side. In this case $N_{ac} = 2a_{r-d}^2 - 2a_{r-d} + 1$ and the overlapping of the ranges of individual actuators is about 73% (less than two actuators per an element of the surface). Finally, the actuators can be arranged over "honeycombs" inscribed into a circle of radius a_{r-d}. In this case $N_{ac} = 1.24a_{r-d}^2$ and the overlapping is about 35%. If the radius of a circle is $2a_{r-d}$ and one more actuator is added at the center, then $N_{ac} = 0.94\, a_{r-d}^2$. Hence, with the same a_{r-d} due to the optimal arrangement of actuators it is possible to substantially decrease (by a factor of 2–4) their number that is very important for large a_{r-d} since namely this case is of interest in practice (see Fig. 4).

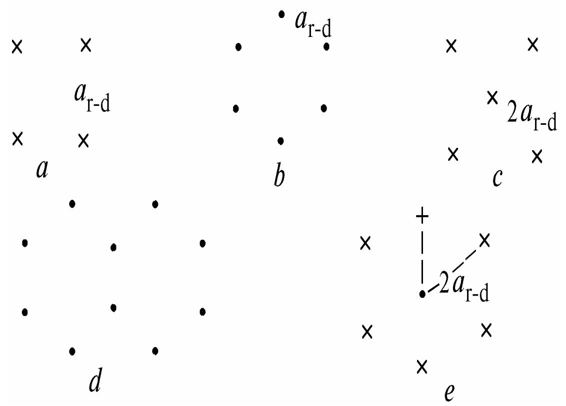

FIG. 3. Different strategies of the actuator arrangement: a) at vertices of a square of a side a_{r-d}, b) around the circles of radii κa_{r-d}, c) at vertices and center of a square of a side $2a_{r-d}$, d) over honeycombs inscribed within the circle of radius $2a_{r-d}$, and e) at the center of the circle.

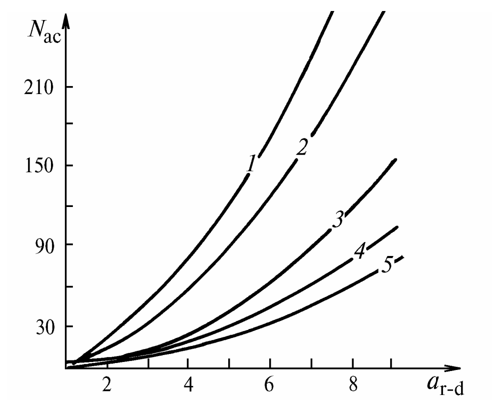

FIG. 4. Total number of actuators vs the parameter a_{r-d} at different approaches to actuator arrangement. Figures at the curves are the same as in Fig. 3.

Consider now the quality of compensation for nonlinear distortions of the Gaussian $f_G = \exp(-(x^2 + y^2)/2)$ or tubular $f_t = (1\sqrt{2})(x^2 + y^2)f_G$ beams passed through a thin defocusing layer[21] which is estimated based on the functional

$$j = \int\int \left(S_{nl} - S_y\right)^2 \, dx \, dy, \qquad (5)$$

where S_{nl} is the additional phase difference caused by optical beam propagation through a nonlinear layer and S_y is the wave front formed with an adaptive mirror. The numerical simulation carried out for compensating for the divergence contributed by the Kerr layer of the medium or layer of the moving medium with a thermal mechanism of nonlinearity, when the actuator arrangement is optimal, shows that the quality of correction of a beam distortion depends on a_{ac}, its profile, and the type of nonlinearity as in the optically dense medium. Let us note that the number of actuators increases in the field of the maximum beam intensity. As an example, the table[21] shows the results of optimization of actuator arrangement and deformation of the mirror with the Gaussian response function near these actuators.

BEAM FOCUSING WITH A SEGMENTED MIRROR

The problems of the beam focusing with a segmented mirror are the least understood by now. In particular, Refs. 4 and 41 and our Refs. 20, 22, and 23 are devoted to this problem. Some of the results are discussed in this section. The laboratory simulation of beam focusing with a segmented mirror was carried out in Ref. 4.

The light beam propagation is described using Eq. (3) with a boundary condition

$$A(0, x, y) = \bar{f}(x, y) \exp(i S(x, y)) , \qquad (6)$$

where S is the wave front and $\bar{f}(x, y)$ is the cross–aperture distribution of optical radiation after its reflection from a segmented mirror

$$\bar{f}(x, y) = f(x, y) \sum_{pq=1}^{M_0} R_{pq}(x, y) . \qquad (7)$$

Here $f(x, y)$ is the initial beam profile, R_{pq} is the reflectance of an individual plate, and M_0 is the number of segments along a single coordinate. For simplicity, we assume that the number of segments along the x and y axes is the same. In this case the segmented mirror introduces the phase shift

$$S_y(x, y) = \sum_{pq=1}^{M_0} \left[\varphi_{xp}(x - x_p) + \varphi_{yp}(y - y_q) + \theta_{pq}\right] R_{pq} , \qquad (8)$$

into the beam wave front. Here θ_{pq} is the longitudinal shift of the segment (p, q) while φ_{xp} and φ_{yq} are its slope angles along the x and y axes, and x_p and y_q are the coordinates of the segment center.

It should be noted that the beam distribution over the amplitude may have narrow dips in the intensity related to the existence of the gaps between individual beamsplitters as well as the gaps formed during their rotation relative to each other. The dips involve difficulties in numerical simulation since near the segment boundary the beam complex amplitude changes more rapidly than it does within the limits of beamsplitters. The situation becomes more complicated because the width of the dips and their location vary with time during the adaptive control of the segmented mirror. Therefore, at present the efficient numerical methods should be developed for modeling such problems (the efficient methods are those whose calculation bulk and time are comparable to the methods for calculating of self–action of the beams without narrow dips in the intensity). One of them is described and tested in Ref. 23.

The method of assigning the function R_{pq} is of importance in simulation. In practice, the reflectance of an individual segment is

$$R_{pq} = \begin{cases} 1 , & |x - x_p| < L_s \cos \varphi_{xp} , \ |y - y_q| < L_s \cos \varphi_{yq} , \\ 0, & \text{in other cases,} \end{cases} \qquad (9)$$

where $2L_s$ is the segment size. For simplicity, the segments are considered to be of the form of square. It is expedient to use the function R_{pq} in analytical investigations when the initial expressions for estimating the quality of formation of the appropriate surface represent integral relations. The smooth functions and those close to Eq. (9) should be employed in numerical experiments.[23]

The next step involves the selection of the appropriate estimate of quality of the light beam focusing with a segmented mirror. The optimal tilts and shifts can be calculated using one of the following two methods.[20,23]

The first method implies the calculation (in particular, using a gradient method) of the optimal wave front S_{opt} at which the extremum of focusing criterion (e.g., the focusing of the beam power received at a target) is attained, and then the segments are arranged so that the functional can be minimized

$$j_s = \int\int (S_{opt} - S_y)^2 \, \kappa(x, y) \, dx \, dy, \qquad (10)$$

where $\kappa(x, y)$ characterizes the transmitting aperture. It should be noted that for small deviations of S_y from S_{opt} the functional in Eq. (10) is related to the value of peak intensity along the beam axis by the Strehl number and is widely used for calculating the effect of errors in formation of the appropriate surfaces with the mirror as well as of uncompensated random aberrations and errors in implementation of optimal perturbations of actuators in flexible mirrors.

The second method includes direct optimization of tilts and shifts of segments to reach the extremal value of the functional chosen for estimating the beam power concentration at the receiver. In particular, the gradient method of optimization makes it possible to organize parallel calculations of functional derivatives over shifts of the segments. It is significant that in the method based on minimizing the functional in Eq. (10) the segment parameters are controlled independently,[20,23] while in the second method based on optimization of the mirror profile all the control channels are interconnected through a complex amplitude of the conjugated problem.

The quality of forming the appropriate surface with a segmented mirror can be estimated based on the functional

$$j_R = \int\int \kappa(x, y) \, |S_{opt} - S_y| \, dx \, dy \qquad (11)$$

which characterizes a uniform deflection of the mirror profile from S_{opt}. Comparison of efficiencies of Eqs. (10)

and (11) shows[22] that the functional j_R is more useful for estimation of the quality of formation.

PHASE CONJUGATION (PC) FOR FOUR–WAVE INTERACTION (FWI)

As is well known, the beam formation with the wave front conjugated to the beam reflected from the receiver can be realized based on such a phenomena as the PC, in particular, the FWI which is the principal approach for attaining the phase conjugation in the IR range. In Refs. 30–33 we analyzed the effect of different factors (inequality of pumping amplitudes, relation between the radii of interacting beams, noncollinearity of their propagation, and so on) on the quality and efficiency of reference wave inversion with regard for (in contrast to the majority of other papers) depletion of pumping waves. Such an analysis can be carried out only by numerical simulation. It is impossible to give a complete discussion for reasons of space. Therefore I take up only two cases here. First, the approximation of the prescribed field widely used in the PC problems gives incorrect dependences of the quality of inversion, e.g., on the length of a medium in the presence of the wave self–action. Second, when the mutual effect of the waves is taken into account the noncollinearity of propagation manifests itself quite differently than in a linear medium. This also leads to incorrect results when approximation of the prescribed field is used. In closing the discussion it should be noted that during the control of the parameters of reference waves it is possible to achieve the 90% reconstruction of the wave front of a reference beam.

TABLE I. Optimization of actuator arrangement (in the first quadrant) and deformation of a mirror during compensation for the Gaussian beam divergence contributed by the Kerr layer $\alpha z = 1$ when $a_{ac} = 0.1$. Represented in the last column is the value of criterion (5).

N	x_1 y_1 θ_1	x_2 y_2 θ_2	x_3 y_3 θ_3	x_4 y_4 θ_4	x_5 y_5 θ_5	x_6 y_6 θ_6	x_7 y_7 θ_7	J
1	0.1673 0.1673 1.81							0.3395
2	0.1675 0.1675 1.80	1.7797 1.6703 0.07						0.3194
3	0.1329 0.1321 1.74	0.4031 0.1681 1.52	0.1681 0.4022 1.56					0.2634
4	0.1328 0.1327 1.73	0.4017 0.1316 1.54	0.1317 0.4016 1.54	0.4008 0.4005 1.41				0.2361
5	0.1328 0.1326 1.72	0.4015 0.1339 1.52	0.1339 0.4016 1.52	1.3791 1.4677 0.06	0.4026 0.4027 1.30			0.2262
6	0.1087 0.1088 1.61	0.3654 0.1310 1.51	0.1309 0.3598 1.51	1.3770 1.3777 0.02	0.2450 0.5411 1.31	0.5430 0.2458 1.31		0.2018
7	0.1072 0.1024 1.62	0.3426 0.1316 1.49	0.1327 0.3547 1.50	1.397 1.476 0.03	0.4061 0.3972 1.32	0.6090 0.1699 1.13	0.1811 0.610 1.14	01887

REFERENCES

1. G.W. Hardy, Proc. IEEE **66**, No. 6, 31–85 (1978).
2. E.A. Vitrichenko, ed., *Adaptive Optics* [Russian translation] (Mir, Moscow, 1980).
3. V.G. Taranenko, Yu.G. Gorokhov, and N.S. Romanyuk, Zarub. Radioelekt. **8**, 19–43.
4. N.N. Artamonov, et al., Izv. Akad. Nauk SSSR, Fiz. **48**, No. 7, 1415–1418 (1984).
5. V.V. Golubev, V.S. Spirazetdinov, and A.D. Starikov, Opt. Spektrosk. **62**, No. 4, 885–890 (1987).
6. A.A. Vasil'ev, A.F. Naumov, and V.I. Shmal'gauzen, Kvant. Elektron. **13**, No. 4, 724–728 (1988).
7. N.D. Ustinov, et al., Kvant. Elektron. **14**, No. 1, 187–189 (1987).
8. N.V. Vysotina, et al., Izv. Vyssh. Uchebn. Zaved., Ser. Fiz. **11**, 42–50 (1985).
9. T. Sato et al., Appl. Opt. **21**, No. 20, 3669–3672 (1982).
10. M.A. Vorontsov, A.V.Kudryashov, and V.I. Shmal'gauzen, Izv. Vyssh. Uchebn. Zaved. Radiofiz. **27**, No. 10, 1419–1430 (1984).
11. Yu.V. Zhulina, Radiotekh. Elektron. **10**, 2061–2070 (1986).
12. M.I. Kovachev, et al., Pis'ma Zh. Eksp. Teor. Fiz. **9**, No. 18, 1113–1115 (1983).
13. J.E. Person and S. Hanes, J. Opt. Soc. Am. **67**, 325–333 (1977).
14. IJ.E. Harvey and G. Callahan, SPIE Proc. **41**, 50–55 (1978).
15. W.B. Bridgs, Appl. Opt. **13**, 291–295 (1974).
16. F.Yu. Kanev and S.S. Chesnokov, Atm. Opt. **2**, No. 3, 243–244 (1989).
17. A.V. Koryabin et al., Atm. Opt. **2**, No. 3, 273–276 (1989).
18. K.V. Shishakov and V.T. Shmal'gauzen, Atm. Opt. **2**, No. 3, 263–265 (1989).
19. A.S.Koryakovskii, V.M. Marchenko, and A.M. Prokhorov, Kratk. Soobshch. Fiz. **4**, 24–26 (1987).
20. A.P. Sykhorukov and V.A. Trofimov, Izv. Akad. Nauk SSSR, Ser. Fiz. **52**, No. 2, 377–382 (1988).
21. A.P. Sukhorukov and T.Yu. Shameeva, Kvant. Elektron. **12**, No. 2, 355–360 (1985).
22. A.P. Sukhorukov and V.A. Trofimov, Opt. Atm. **1**, No. 6, 44–49 (1988).
23. V.A. Trofimov, Izv. Vyssh. Uchebn. Zaved. Radiofiz. **33**, No. 8, 987–989 (1990).
24. A.P. Sukhorukov, V.V. Timofeev, and V.A. Trofimov, Izv. Akad. Nauk SSSR. Ser. Fiz. **48**, No. 7, 1400–1408 (1984).
25. F.P. Vasil'ev et al., in: *Abstracts of Reports at the 8th All–Union Symposium on Laser Radiation in the Atmosphere*, Institute of Atmospheric Optics, Siberian Branch of the Academy of Sciences of the USSR, Tomsk, 1986, Part. **3**, pp. 102–107.
26. A.P. Sukhorukov, V.V. Timofeev, and V.A. Trofimov, Izv. Vyssh. Uchebn. Zaved. Radiofiz. **27**, No. 12, 1514–1524 (1984).
27. A.P. Sukhorukov and V.A. Trofimov, in: *Methods of Mathematical Simulation, Automatization of Processing of Observations and Their Application* (Publishing House of M.V. Lomonosov State University, Moscow, 1986, pp. 105–120.
28. B.Ya. Zel'dovich, N.F. Pilipetskii, and V.V. Shkunov, *Phase Conjugation* (Nauka, Moscow, 1985), 246 pp.
29. V.I. Bespalov and G.A. Pasmanik, *Nonlinear Optics and Adaptive Laser Systems* (Nauka, Moscow, 1986), 134 pp.
30. A.P. Sukhorukov and V.A. Trofimov, Izv. Akad. Nauk SSSR, Fiz. **51**, No. 2, 340–346 (1987).
31. A.P. Sukhorukov and V.A. Trofimov, in: *Phase Conjugation of Laser Radiation in Nonlinear Media* (Publishing House of Physics Institute, Minsk, 1987), pp. 100–105.

32. A.P. Sukhorukov, V.N. Titov, and V.A. Trofimov, Atm. Opt. **2**, No. 10, 933–939 (1989).
33. A.P. Sukhorukov, V.N. Titov, and V.A. Trofimov, Izv. Akad. Nauk SSSR. Ser. Fiz. **54**, No. 6, 1099–1103 (1990).
34. V.A. Trofimov, Atm. Opt. **3**, No. 1, 57–65 (1990).
35. V.A. Trofimov, in: *Adaptive Optics* (Publishing House of the Aviation Institute, Kazan', 1990).
36. V.A. Trofimov, in: *Laser Beams* (Publishing House of the Polytechnic Institute, Khabarovsk, 1988), pp. 8–13.
37. V.A. Trofimov, Atm. Opt. **4**, No. 12, 873–877 (1991).
38. A.P. Sukhorukov, V.A. Trofimov, and T.Yu. Shameeva, in: *Adaptive Optics* (Publishing House of the Aviation Institute, Kazan', 1987), pp. 10–20.
39. A.P. Sukhorukov, V.A. Trofimov, and T.Yu. Shameeva, in: *Laser Beams* (Publishing House of the Polytechnic Institute, Khabarovsk, 1985), pp. 30–36.
40. Yu.N. Karamzin, A.P. Sukhorukov, and V.A. Trofimov, Izv. Vyssh. Uchebn. Zaved. Radiofiz. **27**, No. 10, 1292–1298 (1984).
41. V.E. Kirakosyants et al., Kvant. Elektron. **10**, No. 12, 2485–2486 (1983).