ALGORITHMS OF COMPENSATION FOR THERMAL BLOOMING

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Received September 26, 1991

The basic algorithms of compensation for thermal blooming are considered, the effect of the parameters of optical systems on the nonlinear distortions of laser beams is evaluated, and the optimization of a system is performed. Efficiency and speed of the algorithms of an a priori *(programmable) correction, phase conjugation, and cross–aperture sensing are compared.*

INTRODUCTION

The effect of thermal blooming accompanying the laser beam propagation through the atmosphere results in significant nonlinear distortions of the beams.[1] These distortions can be reduced by means of optimization of the parameters of the optical system as well as using the beam control algorithms, which can be tentatively divided into the methods of phase (*a priori* and adaptive) and amplitude–phase correction.

By optimization of the parameters of the system we understand choosing the radiating aperture, prescribing the optimal distribution of the wave field, preliminary focusing, and choosing the pulse length and the pulse repetition frequency in the case of a pulsed regime of radiation.

A priori phase control of the beam is understood as introduction of pre–distortions in the phase profile based on the information about the state of the atmosphere and about the parameters of the signal. This algorithm is noniterative, and the change in the phase profile is possible only when the recorded parameters vary.

Adaptive phase control is based on prescribing the phase profiles on the basis of the information about the distribution of the wave field in the image plane or on the information about the reflected signal in the plane of the radiating aperture. Depending on the chosen method of control, either the distribution of amplitude and phase or spectral characteristics of the beam are recorded. These algorithms are usually iteratively convergent.

The amplitude phase control differs from completely phase control only by the fact that both the amplitude and phase distributions of the wave field are prescribed upon entering the nonlinear medium based on the measured parameters of the beam.

In the present paper we analize these basic methods of compensation for thermal blooming. Note that to describe the field in the image plane various authors employ different parameters, so we compare in Section 4 the efficiency of correction for only several control algorithms (such as programmable correction, phase conjugation, and cross–aperture sensing).

Since the numerical experiments are widely used to study correction of the self–action effects, a description of a typical computational scheme must be given here. That scheme usually is based on the simultaneous solution of the equation of quasi–optics describing the propagation of radiation and the material equation.[2] Nonlinear properties of the medium are described by the parameter

$$R = \frac{2\kappa^2 a_0^3 I_0}{n_0 \rho C_p V_0} \frac{\partial n}{\partial T}, \qquad (1)$$

which is a function of the average wind velocity V_0. The value a_0 in Eq. (1) is the initial radius of the beam, T is the temperature of the medium, and the rest of notation is generally accepted. The spatial variables of the model are normalized by the initial radius of the beam a_0 in the plane perpendicular to the direction of propagation and by the diffraction length $z_d = \kappa a_0^2$ in the direction of wave propagation. The temporal scale of the problem is the convective time $\tau_V = a_0/V_0$.

The light field in the image plane is characterized by the criterion of focusing $J(t)$ and by the maximum density of radiant power $I_m(t)$

$$J(t) = \frac{1}{P_0} \int\int \rho(x, y)\, I(x, y, z_0, t)\, dx dy, \qquad (2)$$

where P_0 is the total beam power, ρ is the aperture function, and

$$I_m(t) = \max_{x, y} I(x, y, z_0, t). \qquad (3)$$

In what follows we consider the efficiency of correction of thermal blooming using the above–indicated parameters.

1. OPTIMIZATION OF THE PARAMETERS OF THE OPTICAL SYSTEM

The stationary intensity distribution in the focal plane of the Gaussian beam, whose propagation is accompanied by thermal blooming, is well known[3] to be mainly determined by the effect of heat loss due to the wind flow and by defocusing of radiation (see Fig. 1). Prescribing the initial focusing, we can reduce these distortions for collimated beams and relatively small nonlinearity parameters ($|R| < 40$). When the curvature of the phase profile is fixed, the diffraction constriction approaches the reflector with increase of nonlinearity,[3,4] i.e., the optimal value of the parameter of focusing δ_R must differ from its value determined for the linear medium. An empirical formula was derived in Ref. 3 based on the results of calculations which gives the optimal value of δ_R

$$\delta_R = 1/[1 + 0.05\, z|R|]\, z. \qquad (4)$$

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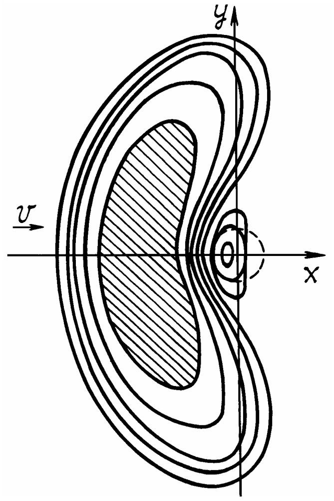


FIG. 1. The stationary distribution of power density in the focal plane of laser emitter (R = –60 and z_0 = 0.25z_d*).*

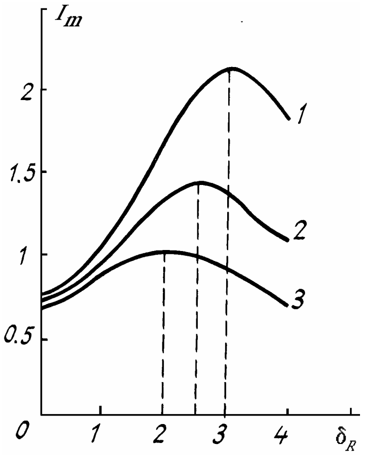


FIG. 2. The maximum power density in the focal plane (z_0 = 0.25z_d) *of the beam vs the parameter of focusing for different nonlinearity parameters R: 1)* –40, *2)* –60, *and 3)* –80.

Figure 2 shows the dependence of the maximum density of power in the focal plane of the beam on the parameter δ_R for different nonlinearity parameters |R|. It can be seen from the graph that the maximum power density $I_{\max}$ can be increased by approximately 40% at the distance $z = 0.25z_d$ if the parameter of focusing is optimized.

With an account of anisotropy of the beam field distribution in the image plane (see Fig. 1) the maximum power density can be increased by cylindrical focusing of the beam along the axis perpendicular to the direction of the movement of the medium.[3] The intensity distribution in the focal plane of the emitter for this case is shown in Fig. 3 (the parameters of the medium and of the beam are identical to those given in Fig. 1). What is most typical here is much less displacement of the energy center of gravity of the beam compared to that shown in Fig. 1, as well as narrowing of the beam cross section at the level of $0.5I_m$ (the hatched area), which indicates the increase of the power density.

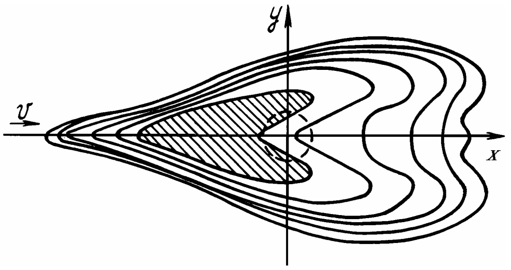
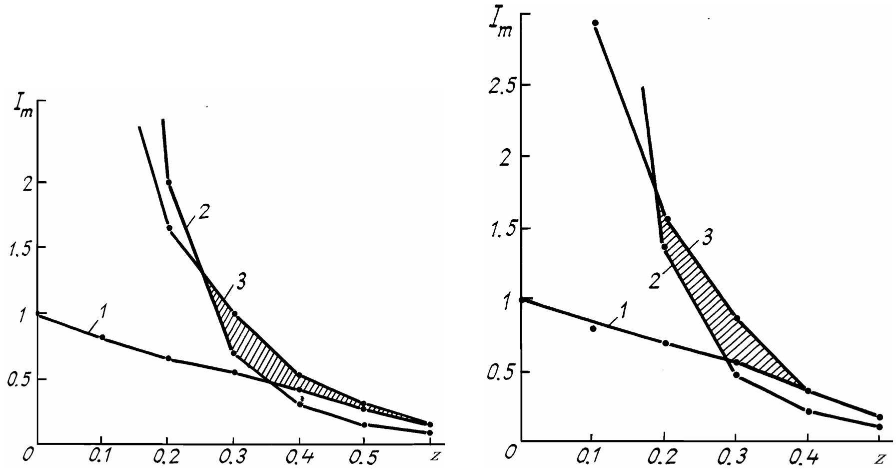


FIG. 3. Power density distribution of the focus of a cylindrical lens. The parameters are the same as in Fig. 1.

To compare the characteristics of different beams, calculations of thermal blooming for three types of Gaussian beams: collimated, focused, and cylindrically focused were performed in Ref. 3. Figure 4 demonstrates the dependence of power density on distance from the receiver for the nonlinearity parameter $R = -60$ (*a*) and –80 (*b*). In both regimes the values of I_m for a cylindrically collimated beam lie above corresponding values for a collimated beam (curve *3* lies above curve *1*) regardless of the path length z, while curve *3* lies above curve *2* (the focused beam) for only limited range of distances (hatched area). With increase of medium nonlinearity this area shifts toward the shorter distances z (see Fig. 4*b*).



a *b*

FIG. 4. The maximum power density vs the distance to the receiver for two values of the nonlinearity parameter R = –60 *(a) and* –80 *(b). 1) collimated beam, 2) focused beam, and 3) cylindrically focused beam.*

One more way of improving the energy characteristics of the beam under conditions of its thermal blooming is the beam scanning around the origin of coordinates.[4,5] A channel with more favorable optical properties is formed in this case. The nonstationary self–consistent problem of programmable scanning was studied in Ref. 4. Figure 5 shows the temporal behavior of the transient processes for two types of beam trajectories: transverse swinging (*a*) and circular scanning (*b*). In both cases the maximum power density I_m, increases with amplitude of the beam displacement, and its behavior is quite complicated and does not follow the trajectory of scanning. The value of I_m can be increased nearly 4–fold for the circular trajectory of scanning. In contrast to the stationary beams, the characteristics of radiation never reach a stationary level for scanning beams.

All the above–considered methods of optimization were analized for beams propagating along the horizontal paths. The problem of optimization of the optical system intended to operate along the vertical paths has its own peculiarity. The energy transport in this case was analyzed in Refs. 5 and 6 for the collimated and focused Gaussian and annular beams. Quantitative analysis of the calculated diffractional pattern shows that propagation of the collimated Gaussian beam is accompanied by the same effects as in the case of horizontal propagation. The substantial differences can be seen in the behavior of the focused beam. For example, while the power of the secondary maximum in the focal spot is about 3–4% of the total radiant power of the beam propagated along the horizontal path, redistribution of power from the main to the secondary maximum takes place along the vertical path as the initial beam power increases.

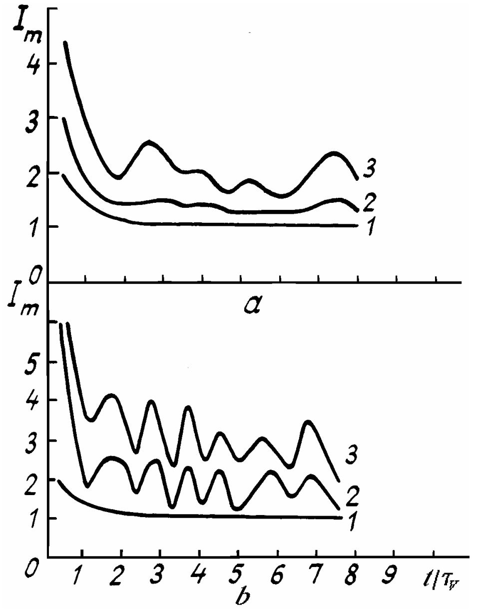


FIG. 5. Transient processes during the beam scanning: a) transverse swinging and b) circular scanning. 1) Stationary beam; 2) scanning with the amplitude $2a_g$, where the parameter $a_g = a_0 z_0$; and 3) scanning with the amplitude $4a_g$.

Quantitative analysis of the results shows that when we proceed from the horizontal to vertical paths, the maximum power density transmitted through the atmosphere increases by more than an order of magnitude for both the collimated and focused beams. Increasing the aperture size also results in an increase of the optimal power. Practically linear dependence of the optimal power of the emitter on the aperture radius of a focused beam is found. The maximum power density at the receiver increases faster than according to the quadratic law.

One more possibility to optimize the beam is the choice of initial amplitude phase distribution. Thus, the result of comparison of the annular beam with the Gaussian focused beam shows that the maximum power density of the Gaussian beam is almost twice less. The annular beam is characterized by a smaller displacement in the direction counter to the wind flow and by more compact diffraction spot. The complicated variations of the amplitude profile were also considered in Ref. 6 while searching for the optimal amplitude profile of the beam was carried out in the classes of Gaussian, super–Gaussian, and hyper–Gaussian beams. It was found that to obtain the maximum power at the target the radiating aperture must be filled at a highest possible density (the hyper–Gaussian and super–Gaussian profiles and the Gaussian profile of double width).

2. ALGORITHMS OF PHASE CONTROL

This section covers the basic methods of phase correction of thermal blooming: *a priori* prescription of the correcting profile and iterative algorithms of phase conjugation and of cross–aperture sensing.

2.1. *A priori* (programmable) correction

The authors of Ref. 7 proposed an algorithm in which pre–distortions determined from the data on the state of the atmosphere and on the parameters of radiation, were introduced in the phase profile of the beam. According to Ref. 7, the correcting phase profile is given by the formula

$$U(x, y) = -\frac{1}{2}\int_{0}^{z_0} \mathrm{d}z\, R(z) \int_{0}^{x} I(\xi, y)\, \mathrm{d}\xi \,, \qquad (5)$$

where $R(z)$ is the nonlinearity parameter of the medium, $I(\xi, y)$ is the normalized profile of the beam intensity in the plane $z = 0$, and z_0 is the path length. As can be seen from this relation, pre–distortions are calculated neglecting diffraction divergence of the beam, i.e., the use of such an approach is justified only for short paths. This method was further developed by the authors of Ref. 8, who suggested to substitute the solution of the linear equation of beam propagation into formula (5) instead of the distribution $I(\xi, y)$.

As will be demonstrated by way of comparison of the correlation methods *a priori* compensation for self–action is comparatively efficient. In addition, the algorithm is not iterative, i.e., the rate of correction is determined only by the time needed to record the parameters, and by the speed of response of the control element of the adaptive system (wavefront corrector).

We should also indicate a number of disadvantages of an *a priori* correction. In particular, errors in measuring the wind velocity and the length of the thermal lens result in a lower control efficiency.[9] In the randomly inhomogeneous medium in the presence of high–frequency fluctuations of the wind velocity along the path, this algorithm appears to be applicable only to quite a narrow range of variations of the parameters of the problem.[10]

2.2. Adaptive control: algorithm of phase conjugation

The method of phase conjugation is based on the principle of optical reciprocity, and the correcting surface is then calculated in each iterative step in the following way:

$$U(x, y, t) = -\varphi(x, y, t - \tau_d) , \tag{6}$$

where φ is the phase of the wave scattered by the object (it is measured in the plane $z = 0$) and τ_d is the characteristic response time of the adaptive system. As can be seen from Eq. (6) the algorithm is not phase conjugated. In order to do it, the amplitude of the beam must also be controlled. In addition, the optical strength of the thermal lens can significantly vary for the time τ_d due to both variations of the phase profile of the beam and of the atmospheric parameters (i.e., we assume that the information about the fluctuations in the refractive index along the path becomes "obsolete"). Despite the negative effect of such factors, application of this method of phase conjugation for low–intense beams[2,11] ($|R| = 7$) or in the case of compensation for the effect of a thin thermal lens[12] results in a significant improvement of energy characteristics of the wave field in the image plane. In the case of compensation for the effect of a distributed nonlinear lens ($|R| \geq 14$ and $z = 0.25\ z_d$) by means of this algorithm, undamped oscillations of the parameters of radiation are found to occur at the object.

To improve the stability of control the authors of Ref. 2 proposed the modified method of phase conjugation whose algorithm can be written as

$$U(x, y, t) = (1 - \alpha)\ U(x, y, t - \tau_d) - \alpha\varphi(x, y, t - \tau_d) . \tag{7}$$

Here $I(\xi, y, t - \tau_d)$ is the phase profile of the beam at the moment $t - \tau_d$ and α is a positive constant smaller than unity. We note that when using algorithm (7) the coefficient α must be chosen since the time of optimization of the beam parameters depends on it.

The other modification of phase conjugation

$$U(x, y, t) = (1 - \alpha(t - \tau_d))\ U_{\max}(x, y) - \alpha(t - \tau_d)\varphi(x, y, t - \tau_d) \tag{8}$$

envisages adaptive change in the coefficient α, which decreases during these iterations resulting in a lower concentration of radiation field in the image plane.[13] The value of $U_{\max}$ in formula (8) is the phase profile that ensures the best results of correction for the observation time. Efficiency and stability of the above–given algorithm were studied in Refs. 2, 11, and 13 in the approximation of stationary refraction, i.e., the authors assumed that the time interval between the successive iterative steps was sufficient for the formation of a stationary thermal lens in the channel of beam propagation (the so–called "slow" adaptive system). Introduction of time dependence in the equation of interaction of the radiation with medium enables one to find the time of search for the extremum of the goal function of control t_{opt} and to estimate the effect of transient processes on the stability of correction.[5,14] This being the case, the use of Eqs. (6) and (7) in a "fast" adaptive system ($\tau_d < \tau_V$) has no principal effect on the convergence of these algorithms. The change in the efficiency and stability of adaptive focusing can only be expected if the characteristic response time of the system is further shortened.

It is of interest to implement algorithm (8) under conditions of nonstationary wind refraction. Its use is based on the choice of the phase $U_{\max}$ and on adaptive decrease of the coefficient α. In order to do this, one needs current data on the change in the parameters of the wave field in the image plane in addition to the recorded phase of the reflected wave. In the course of correction, the oscillations due to the transient processes are then superposed on the variations of the parameters caused by the change in the phase profile. For this reason, in the course of adaptation with the use of the unsteady field, a random phase is stored as $U_{\max}$, and the coefficient α is changed irregularly. For example, it was demonstrated in Ref. 14 that implementation of iterative procedure (8) is possible only with the use of the stationary field. The process of convergence of algorithm (8) is illustrated by Fig. 6.

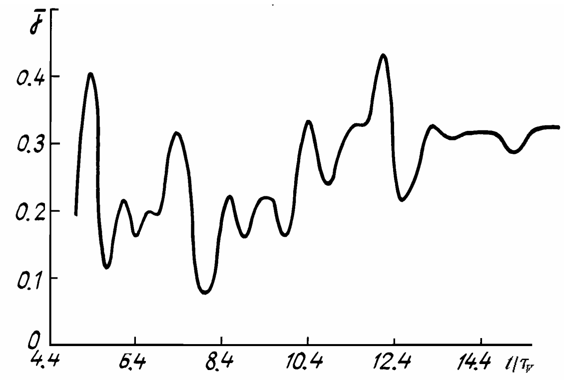


FIG. 6. Change in the focusing criterion $J(t)$ in the process of the adaptive control by the beam. The algorithm of modified phase conjugation (8) was implemented with the use of the stationary parameters of the light field $R = -20$ and $z_0 = 0.5\ z_d$.

When employing the methods of phase correction an actual problem is to optimize the basis of control coordinates (i.e., the problem of choosing the optimal number of the degrees of freedom of the control element of the system). Results of such studies were published by the author of Ref. 15, who investigated the class of the lowest–order Zernike polynomials using algorithm (8), and demonstrated that correction of the lowest–order phase aberrations ensured efficiency of about 80% of the value obtained for an ideal system (without any limitations on the prescribed phase profile) under conditions of moderate nonlinearity. The compensation for self–action for a wider range of variation in the parameters analyzed in Ref. 16 resulted in a conclusion that the optimal number of the degrees of freedom depended on the conditions of beam propagation. In particular, when we proceed to short paths with simultaneous increase of the nonlinearity of the medium, the relative contribution of the third– and fourth–order polynomials increases too.

The problem typical of the phase conjugation method and of *a priori* control by the beam is prescribing the correcting phase profile of the adaptive mirror $U(x, y)$. The accuracy of reproduction of this profile depends on the parameters of the mirror and on the method of approximation. The so–called collocation method was proposed in Ref. 17 according to which the mirror at the point of clamping of servoactuators is displaced at distances equal to the phase shifts at corresponding points. Studies carried out using the numerical model of flexible plate demonstrated that a satisfactory accuracy of the prescribed phase was obtained with the mirror with 8–10 servoactuators. Thus, using such a mirror to implement algorithm (8), the concentration of field in image plane is reduced only by 10–12% compared to the case of the ideal corrector.

Integral methods of phase approximation (for example, the method of least squares[17]) make it possible to decrease by a factor of approximately two the number of servoactuators without decrease in the accuracy of reconstruction of the prescribed surface.

2.3. Adaptive control: the algorithm of cross–aperture sensing

The algorithm of cross–aperture sensing can be written as follows

$$\mathbf{F}(t) = \mathbf{F}(t - \tau_d) + \alpha(t - \tau_d)\ \mathrm{grad}\ J(x,\ y,\ t - \tau_d)\ . \qquad (9)$$

where **F** is the vector of control coordinates, J is the goal function, α is the size of the gradient step. The components of the vector grad J are the derivatives $\partial J/\partial F_i$ ($i = 1,\ldots, N$, where N is the number of the degrees of freedom of the corrector), determined in the course of test variations. As can be seen, to implement this algorithm it is necessary to have the current information about the distribution of filed intensity in the image plane.

The problem of approximating the prescribed phase profile with the mirror does not arise for algorithm of cross–aperture sensing, but similarly to the case of phase conjugation, the efficiency of control depends on the type of control element. The dependence of the quality of compensation on the number of degrees of freedom of the mirror was studied in Refs. 19 and 20. There it was demonstrated that for the correction of moderate nonlinearity on extended paths it is sufficiently to control by the lowest–order polynomials: tilt, focusing, and astigmatism. The use of the mirror of a complicated design is only feasible when the medium is highly nonlinear and the length of the thermal lens is small.

In the study of the correction in the case of nonstationary refraction it was found that the time of "climbing the hill" was about 100 τ_V (Ref. 14) if we control by stationary parameters. When controlling by unsteady parameters of the field there arises a problem of determining the direction of the gradient step, associated with the fact that it is impossible to determine what does actually produce the change in the criterion in the course of test variations – either the small changes in the phase profile or oscillations of the field in the process of forming of the thermal lens. The effect of such factors on the change in the goal function cannot be separated, if test variations are carried out for the time shorter than the characteristic time of the development of the transient processes τ_V. Note that proceeding to the control by the unsteady parameters, the time t_{opt} can be reduced by a factor of approximately 20. The characteristic feature of this algorithm is the nonmonotonous character of change in the beam parameters in the image plane (Fig. 7). This means that it is impossible to adaptively change the size of the gradient step α, i.e., the coefficient must be chosen *a priori*. If this choice is improper, undamped oscillations will arise in the system (curve *2*, Fig. 7).

The effect of interference on the convergence of control can be reduced if the gradient algorithms are substituted by some procedure of search for the extremum based on the simplex–method, which is minutely described in Ref. 27.

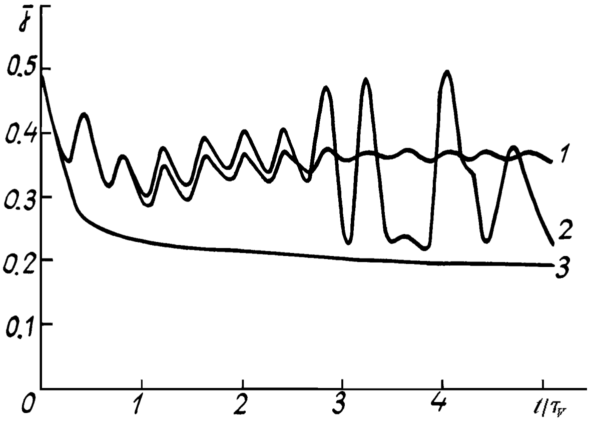


FIG. 7. Change in the focusing criterion J(t) in the process of adaptive control by the beam. Algorithm of cross–aperture sensing implements the unsteady parameters of the light field. $R = -20$ *and* $z_0 = 0.5z_d$*. 1) Gradient step size* $\alpha = 0.5$*, 2)* $\alpha = 1.0$*, and 3) without control.*

3. AMPLITUDE PHASE CONTROL OF THE BEAM

The phase conjugation (PC) algorithm is classified among the methods of amplitude phase control. The beam in the PC system is reflected from a glint point on the object and passes the path in the backward direction (another laser beam may also be used as a reference beam, propagating counter to the sensing beam). The medium inhomogeneities affect the counter beam in exactly the same way as the direct beam. According to the principle of optical reciprocity, the signal with a wavefront being phase conjugate to the wavefront of the reference beam will be optimally focused into the nonlinear medium. In other words, to implement the PC method upon entering the nonlinear medium, one has to form the beam with the necessary amplitude and phase distributions.

Application of this algorithm to the nonlinear medium has a number of peculiarities. In particular, when compensating for the stationary thermal lens, the process of control is iteratively convergent, and in moderately nonlinear media ($|R| = 20$) the maximum values of the goal function are reached in 2–3 steps. With increase of the nonlinearity of the medium ($|R| = 30$) undamped oscillations of field parameters develop in the "slow" adaptive systems and those oscillations can be suppressed only if the time interval between the successive iterative steps is shortened (see Fig. 8).

The phase conjugation was achieved in Refs. 22 and 23 using the effect of Mandel'shtam–Brillouin stimulated scattering (MBSS), which takes place in the active media. The authors of these studies demonstrated the possibility of compensating for thermal defocusing by the MBSS mirrors both under conditions of laboratory experiment and on the basis of the numerical simulation.

The authors of Refs. 24 and 25 considered the amplitude phase control in optical–mechanical systems by means of the phase conjugation achieved in a scheme of a two–mirror adaptive system. That system operated transforming the phase perturbations into the amplitude ones in the process of wave propagation through the space. Controlling the phase of the beam by the first mirror, one can obtain the needed amplitude distribution in the plane of the second mirror. The second mirror forms the phase profile. Note that to realize the PC process in such a system it is necessary to have the information about the phase and amplitude distributions of the reference signal.

The PC algorithm has a number of undisputed advantages, such as the fast response, the high quality of correction of distortions, and the low dependence of its efficiency on the nonlinearity of the medium.[26] However, despite all these advantages, difficulties of instrumental realization of the PC method limit its practical applicability.

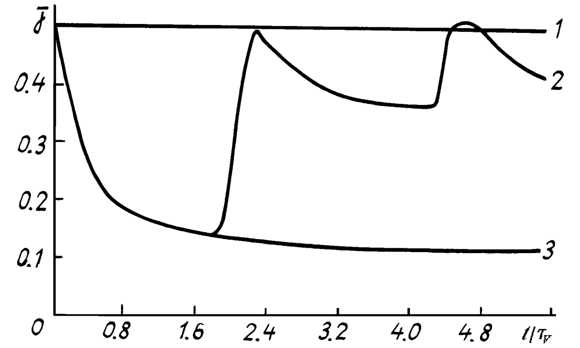


FIG. 8. Algorithm of phase conjugation. $R = -30$ and $z_0 = 0.5z_d$. 1) Caharacteristic time of an adaptive system $\tau_d = 0.3\tau_V$, 2) $\tau_d = 1.8\tau_V$, and 3) without control.

4. COMPARISON OF THE ALGORITHMS OF CORRECTION FOR SELF–ACTION

The properties of algorithms determined from the numerical experiments are listed below in Table I.

Such parameters of the algorithms as the time of optimization (the time of search for the extremum of the goal function t_{opt}) and the resulting value of the focusing criterion J_{opt} are given for the parameters $|R| = 20$ and $z_0 = 0.5z_d$. The initial value of J (collimated beam) is 0.19 in this case.

Since the algorithm of programmable correction is not iterative (the time of prescribing of the optimal phase is determined by the time needed to record the parameters of the atmosphere and of the beam). The time required for the formation of the stationary thermal lens is indicated here as t_{opt}. The characteristics of aperture cross–sensing and of algorithm (7) are given for the control by unsteady field. Modified phase conjugation (8) is based on the stationary parameters.

We can conclude from the table that the considered methods of correction significantly differ in their principal characteristics.

TABLE I. Characteristics of the algorithms for correction of self–action.

Control algorithm	Control element of the adaptive system	Information needed to perform control	Type of convergence of control algorithm	Time of search for extremum of the goal function $\tau_{\mathrm{opt}}/\tau_V$	Resulting value of the focusing criterion J_{opt}
A priori correction (5)	Adaptive mirror	Parameters of the beam, atmospheric parameters, and the path length	*A priori* determination of the phase profile	5	0.33
Phase conjugation (6)	Adaptive mirror	Phase of the reflected wave (in the plane $z = 0$)	Iterative and divergent in highly nonlinear media ($|R| \geq 10$)	The undamped oscillations develop in the system for $|R| = 20$	
Modified phase conjugation (7)	Adaptive mirror	Phase of the reflected wave ($z = 0$) and phase profile of the beam in the preceding iteration step	Iterative and divergent for improperly chosen coefficient	7	0.32
Modified phase conjugation (8)	Adaptive mirror	Phase of the reflected wave ($z = 0$), maximum goal function, and corresponding phase profile	Iterative convergence	20	0.33
Cross–aperture sensing	Adaptive mirror	Current value of the goal function	Iterative and divergent for improperly chosen coefficient	5	0.34
Phase conjugation in a two–mirror adaptive system	Two mirrors separated by the space filled with a linear medium	Amplitude and phase distributions of the reflected wave in the plane $z = 0$	Convergence dependent on the speed of response of the adaptive system	Goal function remaining practically unchanged	0.50

The most promising method is apparently the phase conjugation method although its wide application is limited by difficulties of its instrumental realization.

The algorithms of the adaptive phase control have approximately the same efficiency of correction for thermal blooming. The minimum time of correction t_{opt} is found for cross–aperture sensing.

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