AMPLITUDE PHASE BEAM CONTROL WITH THE HELP OF A TWO-MIRROR ADAPTIVE SYSTEM

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A method of compensating for thermal blooming of laser beams based on the algorithm of phase conjugation is studied. A numerical model of a two-mirror adaptive system based on the phase conjugation algorithm is constructed. The quality of correction of a thermal lens is evaluated as a function of system parameters. It is shown that the efficiency of control depends on the number of Zernike polynomials reproduced by mirrors.

The methods of phase correction of thermal blooming have been already investigated quite extensively.[1-3] The main properties of control algorithms have been evaluated and the correction of the thermal lens has been studied under laboratory conditions.[4,5] We can conclude from the data of these studies that phase control is an efficient method of compensation for thermal blooming. At the same time, it also has a number of important disadvantages typical of all algorithms. In particular, although an essential relative improvement of the quality criteria of radiation can be obtained with the help of phase control (e.g., the power entering the aperture of a given size can be increased by a factor of 5 or even more[6]), the resultant values of such criteria remain far below those for the beam propagating through a linear medium. It has been demonstrated in Ref. 6 that the correction of the distributed thermal lens looses its meaning for strong nonlinearity of the medium.

The second important disadvantage of the methods of phase correction is their low response rate. In the presence of the high frequency pulsations of the wind velocity in the medium, low response rate results in lower efficiency of control.[7] This is so because the thermal lens induced in the path by the beam strongly varies with the changes in the wind velocity. For this reason to ensure the high quality of correction of this lens its effect should be compensated for the time shorter than the period of velocity pulsations.

It will be demonstrated below that the effect of these factors can be reduced when we proceed to amplitude phase methods of correction of thermal blooming of the beam, in particular when we implement the algorithm of phase conjugation (PC).

1. MODEL OF BEAM PROPAGATION UNDER CONDITIONS OF NONSTATIONARY WIND REFRACTION

With an account of the thermal blooming of the beam its propagation through the nonlinear atmosphere is described by a system of differential equations in the complex amplitude of the field E and in the temperature of the medium T (Ref. 3)

$$2ik\frac{\partial E}{\partial z} = \frac{\partial E}{\partial x} + \frac{\partial E}{\partial y} + 2\,\frac{\kappa^2}{n_0}\frac{\partial n}{\partial T}\,TE\ , \tag{1}$$

$$\frac{\partial T}{\partial t} + (\mathbf{V}_\nabla)T = \frac{\alpha I}{\rho C_p}\ . \tag{2}$$

Wind velocity $\mathbf{V}$ is, in general, a random value. Solving this problem we assume that $\mathbf{V}$ has a constant component $\mathbf{V}_0$ along the OX axis and random components $\delta\mathbf{V}_x$ and $\delta\mathbf{V}_y$.

Nonlinear properties of the medium are described by the parameter

$$R_V = \frac{2\kappa^2 a_0^3\,\alpha I_0}{n_0\rho C_p|V|}\frac{\partial n}{\partial T}\ . \tag{3}$$

Here a_0 is the initial radius of the beam. Notation used here is generally accepted.[3,6,7]

The spatial scale of the problem along the axis of beam propagation is the diffraction length $z_d = \kappa a_0^2$, and in the transverse direction – the initial radius of the beam a_0. It is convenient to choose the convective time $\tau_v = a_0/V_0$, determined by the average wind velocity V_0, as the temporal scale of the problem.

The distribution of the field in the image plane is characterized by the criterion

$$J = \frac{1}{P_0}\int\int \rho(x,\,y)\,I(x,\,y,\,z_0,\,t)\,\mathrm{d}x\mathrm{d}y\ , \tag{4}$$

which is proportional to the fraction of power entering the aperture of a given size. The function

$$\rho(x,\,y) = \exp\,(\,-\,(x^2 + y^2)/S_t^2)$$

entering into Eq. (4) is the aperture function, S_t is the aperture radius, and P_0 is the total power of the beam.

2. COMPENSATION FOR THERMAL LENS BASED ON THE ALGORITHM OF PHASE CONJUGATION

To illustrate the efficiency of methods of amplitude phase control, we consider the problem of correction of blooming based on the phase conjugation algorithm. The phase conjugation is achieved with the use of the collimated beam as a reference signal. In this case the parameters of the beam after it has passed the nonlinear medium must be equal to the parameters of the collimated beam, given that the compensation is complete. In particular, the parameter J for the path $z = 0.5\,z_d$ must be equal to 0.5 (all further calculations were performed for the path of length 0.5 z_d).

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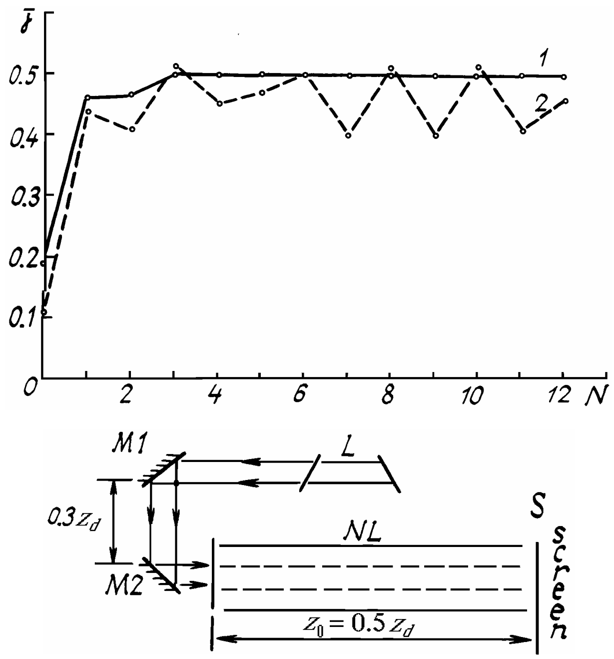

FIG. 1. Compensation for thermal blooming based on the PC algorithm in the case of stationary wind refraction. J is the focusing criterion, N is the number of iterative steps, and $z_0 = 0.5\ z_d$. *1)* $|R_v| = 20$ *and 2)* $|R_v| = 30$.

The change of the criterion J in the course of the iteration process is illustrated by Fig. 1 for $|R_v| = 20$ and 30. We consider the case of correction of stationary wind refraction. It can be seen that for $|R_v| = 20$ the maximum power density is obtained at the object in 2–3 iterations then the criterion remains practically unchanged. If the medium nonlinearity is increased ($|R_v| = 30$) the undamped oscillations of power density are found to occur at the object. They are caused by the fact that in each iteration step the beam induces the thermal lens different from the lens induced in the preceding iteration step. Proceeding to the control under conditions of nonstationary refraction, we can reduce the relative changes of this thermal lens decreasing the time period between successive iterations. Numerical experiments demonstrated that when the time interval between these steps was shortened up down $0.3\ \tau_v$, oscillations of the criterion vanished, and practically identical field concentrations were achieved at the target for both nonlinearity parameters $R_v = -20$ and -30.

Thus using the PC methods in the above indicated range of variation of the parameters, we find that the resultant values of the criterion J are independent of the level of nonlinearity of the medium. This property gives an important advantage to the PC method over the methods of phase correction of thermal distortions.

3. REALIZATION OF THE PHASE CONJUGATION METHOD WITH THE HELP OF A TWO–MIRROR ADAPTIVE SYSTEM

To implement the PC algorithm, we must prescribe the beam with the amplitude profile corresponding to that of the reference signal and with the phase distribution whose sign is opposite to the sign of phase distribution of the reference signal. As it was demonstrated in Refs. 8 and 9, such a procedure could be implemented with the help of a two–mirror adaptive system (Fig. 2). Here *M1* and *M2* are the flexible mirrors, *L* is the laser radiation source, and *NL* is the nonlinear medium. The beam is focused onto the plane *S*. The reference signal is formed by the collimated beam propagating in the direction counter to the initial beam. It is assumed that the counter beam induces no thermal lens in the medium. Parameters of the reference signal are controlled in the plane of the corrector *M2*. Controlling the phase of the beam in the plane *M1*, we can obtain the change of its amplitude in the plane *M2*. The necessary phase profile is formed by the mirror *M2*.

The techniques are well–known for phase control of the beam and for forming the needed phase profile with a flexible mirror.[6,7] Thus, we dwell in ample detail on the formation of the amplitude profile of the beam with the help of the phase control. An iterative procedure proposed in Ref. 9 has the high accuracy but slower rate of control. At the same time the necessary amplitude profile can be formed in a single iteration. In order to do this, it is necessary to fill the space between the mirrors *M1* and *M2* with a linear medium and keep this space fixed in the course of control. In this case the parameters of the beam in the plane *M2* correspond to phase aberrations in the plane *M1*. In particular, when controlling by tilt of the phase surface of the beam in the plane *M1* we obtain the displacement of the position of its energy centroid in the plane *M2*, and when controlling by focusing and astigmatism we obtain the change in the beam energy radii along the *OX* and *OY* axes. If coma is prescribed, we obtain a crescent–shaped beam in the plane *M2*. In other words, if the correspondence is found measuring the parameters of the reference beam in the plane *M2* and controlling by amplitude of the beam with the help of the mirror *M1* and by phase with the help of the mirror *M2*, we can obtain a beam with needed distribution of both amplitude and phase upon entering the nonlinear medium.

4. EFFICIENCY OF THE CORRECTION OF BLOOMING WITH THE HELP OF A TWO–MIRROR ADAPTIVE SYSTEM

The dependence of the efficiency of correction on the number of the lowest–order aberrations reproduced by the corrector *M1* is shown in Fig. 3 for the case of stationary thermal blooming of the beam. The corrector *M2* is assumed to be ideal. The result obtained with the use of the first flat mirror corresponds to a complete phase control of the beam (the algorithm of phase conjugation).

It can be seen from the data shown here that implementation of the amplitude control with the help of a two–mirror adaptive system yields the field concentration obtained with the use of the ideal phase conjugation.

Similar to the case of ideal phase conjugation, the result of compensation for thermal blooming with the help of a two–mirror adaptive system depends but insignificantly on the medium nonlinearity (Fig. 4). When the module of the nonlinearity parameter $|R_v|$ increased from 20 to 30, the resultant values of quality criterion decreased by 1%. Note for comparison that when implementing the algorithm of phase conjugation, the decrease of field concentration is about 27% when R_v varies within the same limits (See Fig. 4).

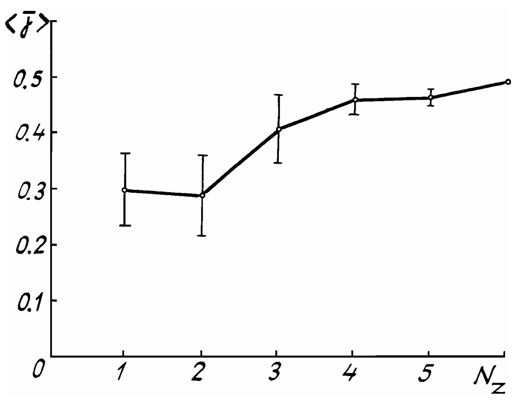

FIG. 3. The quality of correction of thermal blooming vs the number of Zernike polynomials reproduced by the first corrector (two–mirror adaptive system) under condition of stationary wind refraction $R_v = -20$ and $z_0 = 0.5\, z_d$. <J> is the criterion of focusing averaged over 30 *iterative steps. N_z is the number of the lowest–order Zernike polynomials reproduced by the corrector M1: $N_z = 1$ refers to a flat mirror; $N_z = 2$ refers to tilt; $N_z = 3$ refers to focusing and astigmatism; $N_z = 4$ refers to tilt, focusing, and astigmatism; $N_z = 5$ refers to tilt, focusing, astigmatism, and coma; $N_z = 6$ refers to ideal phase conjugation.*

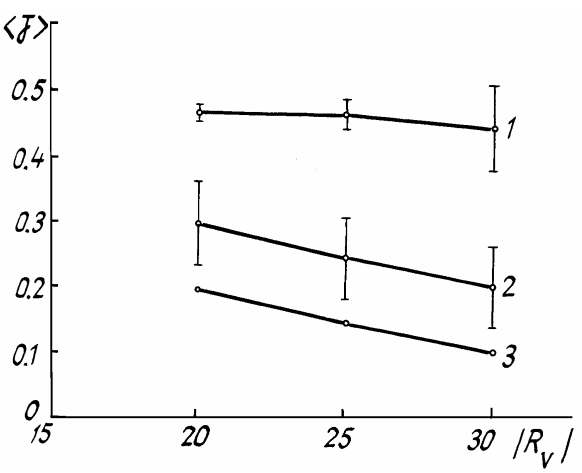

FIG. 4. The resultant values of the criterion of focusing J averaged over 30 *iterative steps vs the nonlinearity of the medium in the case of stationary refraction at $z_0 = 0.5\, z_d$. 1) two–mirror system, 2) phase conjugation and 3) without control.*

Comparatively low response rate of phase control results in a decrease of the efficiency of a beam control in the media with large–scale inhomogeneities. Thus, when the period of pulsations of wind velocity T_v decreases from 5 τ_v to 2 τ_v, the corresponding decrease of the field concentration is about 14% (Fig. 5). Curve *2* in Fig. 5 shows the use of cross–aperture sensing. In the case of amplitude phase correction (Fig. 5, curve *1*) the efficiency of control is practically independent of the period of pulsations.

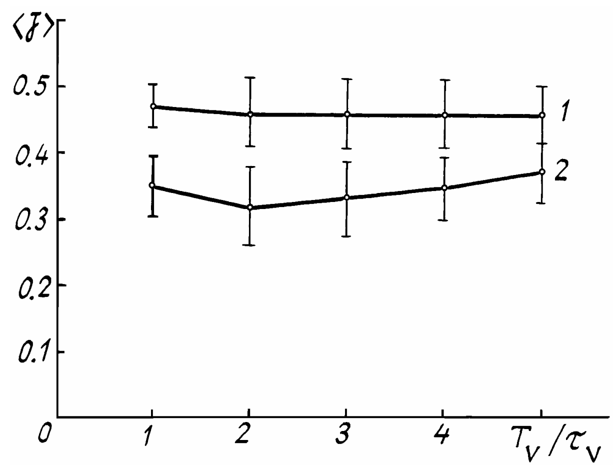

FIG. 5. Adaptive control in the presence of pulsations of the wind velocity. The quality of correction of thermal blooming vs the period of wind velocity pulsations T_v $z_0 = 0.5\, z_d$ and $\langle R \rangle = -20$. The interval of time averaging is about 40 τ_v. *1) adaptive two–mirror system and 2) algorithm of cross–aperture sensing.*

5. MAIN RESULTS

1. The two–mirror system demonstrates higher efficiency of correction of the thermal lens over the algorithms of phase control for the above–considered cases (stationary wind refraction and nonstationary refraction in the randomly inhomogeneous medium).

2. The quality of correction of the thermal lens with the help of the two–mirror adaptive system remains practically independent of the medium nonlinearity in the above–studied range of variations of the parameters of the regular medium.

3. The efficiency of correction of the thermal lens changes insignificantly in the randomly inhomogeneous nonlinear medium when the frequency of pulsations of wind velocity varies.

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