Adaptive control over radiant fluxes of a multibeam laser

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An adaptive system for tilt correction of wave fronts of a multibeam laser is simulated numerically. A segmented mirror, each segment of which controls its own radiant flux is used as a control element. A model of the system is developed, and the maximum permissible dimensions of a diaphragm in the measuring channel that provides a required quality of correction are determined. The results of numerical study have been obtained for a 16-beam laser.

Introduction

Lasers of some types generate tubular beams formed by several radiant fluxes. Such beams conserving their shape along the entire path can be obtained using wide-aperture lasers with an active volume having an annular cross section, or the so-called coaxial lasers.[1] With tubular beams, we can generate a "clearing-up" wave on the sounding path with the sensing radiation inside a clearing-up channel.[2,3]

Fluxes forming the tubular beams are generated by multipass oscillations (M-modes); they propagate extrameridionally along the beam path.[1] Peculiarities of the spatial structure of M-modes of a wide-aperture laser (Jupiter laser) were considered in Ref. 4, and the laser design and experimental results are given in Ref. 5.

An advantage of this laser is phasing-in of all fluxes forming the tubular beam, because each of them is formed by the same M-mode. If this laser is used in lidar systems, there is no need in spatial separation of a beam (in order to control every its part with a separate corrector).

Lasers operating at M-modes are characterized by varying tilts of wave fronts of an individual beam due to random and unsteady inhomogeneities of the active medium. In the Jupiter laser, the experimentally measured period of fluctuations is from 0.1 to 2 s (Ref. 5). The use of such lasers for atmospheric sensing apparently requires adaptive systems for stabilizing spatial characteristics of radiation.

In this paper, we present the results of numerical simulation of an adaptive system for tilt correction of wave fronts of multibeam radiation generated by the Jupiter laser.

1. Statement of the problem

A two-channel system can be used as a version of the adaptive system for a multibeam laser. In this system, the first channel is to provide for the initial parallelism of all beams at the entrance into the medium, and the second channel is responsible for their following adaptation to atmospheric distortions. Certainly, a version that both problems are solved in one channel is also possible.

For the methodological reasons, at the initial stage of our study it is worth considering the operation of each channel separately. Therefore, the main purpose of this work is to analyze peculiarities arising in the first channel – channel for tilt correction of wave fronts of individual beam at the laser output.

The number of radiant fluxes of the M-mode generated in the Jupiter laser can be rather easily regulated with the intracavity diaphragms.[5] Experimental studies show that the laser generating one 16-beam mode is convenient for separate control over fluxes. Parallelism of all beams at the laser output (at the entrance into the sensed zone) can be evaluated using the known method, i.e., from the quality of focusing of some part of radiation within a small diaphragm installed in the measuring system of the adaptation channel. Because the adaptation conditions of multibeam lasers are poorly understood, in this paper we consider the following problems:

1. Properties of a focusing functional;
2. Control algorithm and behavior of the system at adaptation;
3. Influence of the diaphragm on the quality of adaptation.

2. Structure of the system and derivation of the equation for focusing functional

The adaptive system under study is constructed following a standard scheme as shown in Fig. 1. To correct for tilts of the wave fronts of 16-flux M-mode of the laser *1*, a 16-segment system *2* of reflectors–piezocorrectors is used. Upon passage through the correctors and beam-splitter *3*, a part of radiation enters into the measuring channel. Focusing system *4* provides radiation focusing in the plane of diaphragm *5*, through which the radiation is received by the photodetector *6*. The signal from the photodetector output comes to the measuring and computing unit *7* that generates control signals for piezocorrectors.

The experimental results from Ref. 6 indicate that non-parallelism of the initial beams of this laser is

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mostly caused by their mutual displacements in sagittal planes. Displacements in the meridional planes are insignificant. In this connection, it is taken that the design of segmented reflectors–piezocorrectors provides their tilts only with respect to the axes lying in the plane of each segment and passing through the center of the whole system of reflectors.

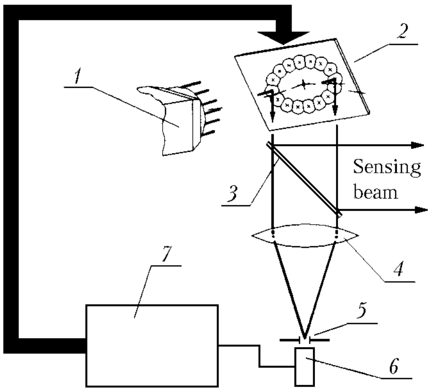

Fig. 1. Tilt correction system for wave fronts of Jupiter multibeam laser.

It is convenient to evaluate the focusing quality using the Strehl number or, in more general case, the focusing functional.[7,8] This functional is determined by the ratio of the power P of radiation passing through a small diaphragm set at the system focus to the same power P_0 at exact focusing. As applied to our case, it can be found from possible positions of beams in the focal plane of the system (Fig. 2), where cross section of each beam can be considered as circular. The experimental results show that "traces" of beams in this plane can move under the effect of destabilizing factors and control actions practically only along the diaphragm radii. That is why we perform the further analysis in the polar coordinate system.

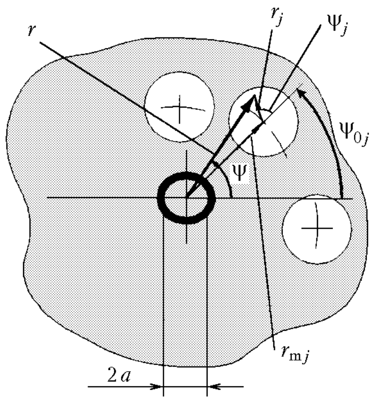

Fig. 2. Radiant fluxes in the diaphragm plane.

To simplify the final equations, we believe that the distribution of the amplitude A_j in the cross section of each beam is Gaussian and the same for all beams, because, as was already mentioned, all beams are generated by the same M-mode:

$$A_j = \mathrm{e}^{-(r_j/W)^2}, \tag{1}$$

where W is the cross section radius of each beam in the diaphragm plane; r_j is the current radial coordinate of a point in the beam cross section, j is the beam number ($j = 1, 2, \ldots, 16$).

From geometrical considerations that are clear from Fig. 2, it is easy to derive the equation for r_j:

$$r_j = \sqrt{r^2 + r_{\mathrm{m}\,j}^2 - 2\,r\,r_{\mathrm{m}\,j}^2 \cos(\psi - \psi_{0j})}, \tag{2}$$

where r and ψ are the current radius and polar angle (integration variable); ψ_{0j} is the angle of the central position for each beam in the diaphragm plane; ψ_j is the angular coordinate of a current point in the coordinate system of each beam; $r_{\mathrm{m}\,j}$ are the distances between the beam centers and the center of the diaphragm.

We believe that the beams are focused in the plain of waists, i.e., in the plain where their cross sections are minimal. In this cross section, the wave front is plain, but, in each beam, it is inclined to the focal plane at some angle, whose tangent is equal to the ratio of R_m to f, where R_m is the mean radius of the radiation ring at the entrance into the focusing system, and f is the focal length of the system. In this case, the plane of the wave front is orthogonal to the propagation axis of each beam. Therefore, the beam phase in the focal plane (in the coordinates r_j and ψ_j) varies as

$$\Phi_j(r_j, \psi_j) = \frac{2\pi}{\lambda}\, r_j \cos \psi_j \, \frac{R_\mathrm{m}}{f}\,. \tag{3}$$

This equation is valid if we assume that the phase of the wave front is zero at the axial point of each beam in the focusing plane. Because usually $f \gg R_\mathrm{m}$, we can neglect eccentricity of the beam cross sections, assuming that the field distribution is axially symmetric with the amplitude determined by Eq. (1).

From Fig. 2 we can also readily derive the equation

$$\cos \psi_j = \frac{r^2 + r_j^2 - 2r\,r_j}{2r\,r_j} \cos(\psi - \psi_{0j}) - \frac{r_{\mathrm{m}\,j} \sin(\psi - \psi_{0j})}{r_j} \sin(\psi - \psi_{0j}). \tag{4}$$

The equation for power P within the diaphragm has the following form:

$$P \approx \int\limits_0^a \int\limits_0^{\psi_{\max}} \left| \sum_{j=1}^{2N} A_j(r,\psi)\, \mathrm{e}^{i\Phi_j(r,\psi)} \right|^2 r\,\mathrm{d}r\,\mathrm{d}\psi, \tag{5}$$

where a is the diaphragm radius; $\psi_{\max}$ is equal to 2π in the general case.

According to Refs. 4 and 5, N determines the number of radiation spots on the laser output mirror. For our case $N = 8$ (16 beams).

The equation for the focusing functional can be presented as

$$J_d = P/P_0, \quad (6)$$

where P_0 is the power of radiation passing through the diaphragm for the case that all beams converge at the diaphragm center ($r_{m\,j} = 0$).

3. Properties of the focusing functional

To justify the choice of the adaptation algorithm, we should first reveal the behavior of the focusing functional.

Two variants of control are possible in the considered system. In the first variant, each beam is driven to the diaphragm center after complete convergence of the previous one. In the second variant, all the beams are driven to the diaphragm center, and every control step for a current beam is made once the regular step for the previous beam has been completed. The first variant is called the algorithm of sequential control, and the second variant is called the algorithm of parallel control.

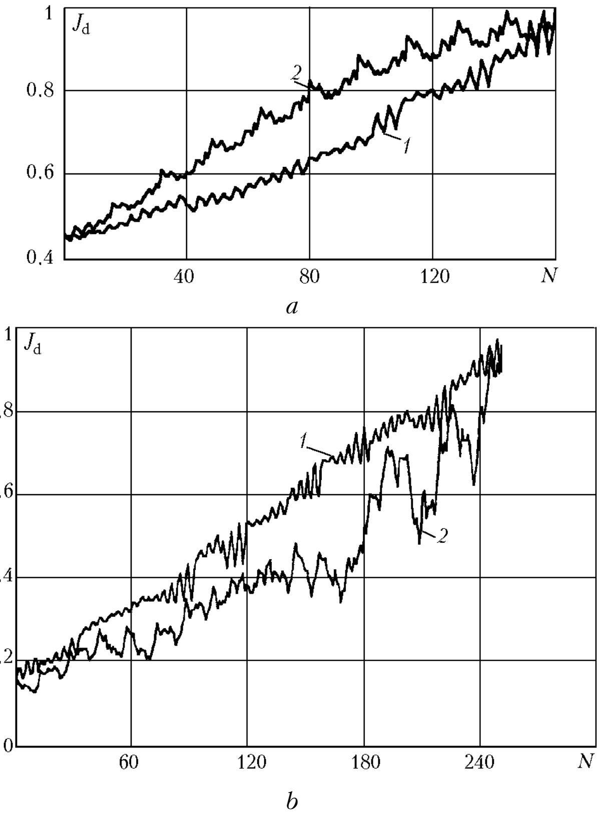

Fig. 3. Dependence of the focusing functional on the step of $r_{m\,j}$ change: the same initial position of beams in the diaphragm plane (*a*) and random initial position of beams (*b*); sequential algorithm (*1*) and parallel algorithm (*2*).

To evaluate the properties of the focusing functional, we have developed a program to compute the values by Eq. (6) at a monotonic change of the distance between the diaphragm center and the center of the *j*th beam. The results are shown in Fig. 3. For each beam, the value of $r_{m\,j}$ was forcedly decreased from some initial value to zero with the step of 0.02 mm. The numbers of steps are shown along the abscissa. The plots are drawn for both variants (sequential and parallel) of $r_{m\,j}$ change for two cases: the same initial position ($r_{m\,j\,in} = 0.2$ mm) of all beams in the diaphragm plane and arbitrary initial position of beams in the diaphragm plane. In the first case (Fig. 3*a*; the same initial position of the beams), 160 computational steps are needed to drive the beams to the center (10 steps in changing $r_{m\,j}$ are needed for each beam to reach the center of the diaphragm). In the second case (taking into account that $r_{m\,j\,in}$ varies in the diaphragm plane from 0 to 0.5 mm [Ref. 5]), the dependence shown in Fig. 3*b* for one of the random sets of $r_{m\,j\,in}$ involves 251 steps of $r_{m\,j}$.

From the computed data shown in Fig. 3 it follows that the focusing functional at varying $r_{m\,j}$ has one global maximum and quite few local ones. The dependences are essentially nonmonotonic. However, the sequential algorithm is characterized by lower irregularity of J_d as a function of $r_{m\,j}$ as compared with the parallel one.

Thus, our computations indicate that for this system it is worth using the sequential control algorithm. Besides, it is clear that the use of a simple gradient method for adaptation is inefficient, since this method provides the ascent only on the closest maximum.

4. Control algorithm and behavior of the system at adaptation

The essentially nonmonotonic behavior of the focusing functional in response to the control actions significantly complicates choosing the control algorithm. The value of the focusing functional J_d depends on the mutual arrangement of the beams. In our case, at the given diaphragm radius, the functional J_d depends on 16 variables $r_{m\,j}$. At the sequential method of control over each beam, J_d for the beam is a function of only one variable. Other beams in this case do not change their position. Therefore, it is convenient to use the value of the introduced trial distortion u, such that

$$r_{m\,j} = r_{m\,j\,in} - u, \quad (7)$$

($r_{m\,j\,in}$ is the initial random position of the *j*th beam), rather than the current position of the beam center $r_{m\,j}$, as a variable, with respect to which the maximum of J_d is sought.

The process of adaptation reduces to the search for the global minimum J^* of the function $J(u) = -J_d(u)$ within a given accuracy ε:

$$\min_{1 \le p \le n} J(u_p) \le J^* + \varepsilon, \quad (8)$$

where u_p are the values of the variables u in the process of adaptation; p is the serial number of an iteration; n is the number of iterations.

To find the minimum of $J(u)$, we used the method of coverage[9] that requires determination of the Lipschitz constant L. Estimates show that $L = 3.97$ for the focusing functional calculated by Eqs. (1)–(6). In computations we took $L = 4$. The accuracy of computations was chosen to be $\varepsilon = 0.005$. In accordance with the sequential algorithm, for each beam we calculated such a position of its center, at which J_d achieved maximum, although, as became clear in the process of simulation, this position did not correspond to the diaphragm center the process was finished after completion of the control over the 16th beam.

In numerical simulation, we used the following parameters: beam radius at the waist $W = 0.3$ mm, laser radiation wavelength $\lambda = 10.6$ mm, focal length of the beam focusing system $f = 304$ mm, radius of the radiation ring at the entrance into the focusing system $R_m = 40$ mm, and the diaphragm radius $a = 0.01$ mm. Table gives the results of simulation of the adaptive system by the above-described algorithm.

Table

Beam number	Number of adaptation steps	$r_{m\,j\,in}$, mm	$r_{m\,j\,f}$, mm	J_d	$\psi_{j\,in}$	$\psi_{j\,f}$
1	29	0.08	0.042	0.058	π/8	π/8
2	25	0.06	0.041	0.083	2π/8	2π/8
3	26	0.18	0.035	0.124	3π/8	π + 3π/8
4	24	0.10	0.04	0.181	π/2	π + π/2
5	25	0.24	0.036	0.262	5π/8	π + 5π/8
6	30	0.06	0.038	0.326	6π/8	π + 6π/8
7	27	0.20	0.039	0.353	7π/8	π + 7π/8
8	22	0.10	0.04	0.434	π	2π
9	29	0.04	0.039	0.436	9π/8	π/8
10	29	0.04	0.039	0.438	10π/8	2π/8
11	26	0.28	0.04	0.486	11π/8	11π/8
12	34	0.04	0.037	0.483	3π/2	12π/8
13	30	0.06	0.041	0.573	13π/8	13π/8
14	31	0.16	0.042	0.758	14π/8	14π/8
15	30	0.18	0.044	0.881	15π/8	15π/8
16	36	0.06	0.038	0.999	2π	2π

As was already mentioned above and as it follows from the tabulated data, the beams are finally not at the center of the diaphragm, but at some distance from it roughly equal to 0.04 mm. Nevertheless, although the algorithm used does not allow us to obtain the exact focusing of the beams at the center of the diaphragm, spatial characteristics of radiation are significantly improved.

5. Influence of the diaphragm on the quality of adaptation

The evaluation of the quality of focusing by use of Strehl criterion involves zero-size diaphragm in the measuring channel, because, strictly speaking, the Strehl number is determined by the axial intensity of radiation, i.e., exactly at the center of the diaphragm. In actual systems, the diaphragm cannot be very small because of the requirement that the recorded power markedly exceeds the background level. In this connection, a question arises on up to what values can we increase the size of the diaphragm without the loss of the focusing quality.

Numerical experiments show that the permissible dimensions of the diaphragm are different at different parameters of the beams (number of beams, size of their cross sections in the diaphragm plane, wavelength, etc.). Therefore, the corresponding studies should be performed in every particular case.

As an example, Fig. 4 shows the focusing functional J_d (after the end of the adaptation process) as a function of the diaphragm radius. In this computation, we used the same parameters as in simulating the sequential algorithm (see Table) at three independent initial distributions $r_{m\,j}$ of the beams.

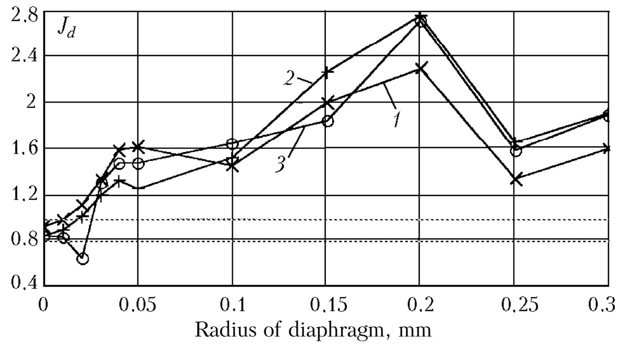

Fig. 4. Focusing functional (as the adaptation process is completed) as function of the diaphragm radius. Plots *1*, *2*, and *3* correspond to different initial positions of the beams.

As is seen from Fig. 4, at the diaphragm radius $a \approx 0.2$ mm, the value of the focusing functional J_d becomes markedly larger than unity, i.e., exceeds the value of J_d at the "zero" position of centers of the beams. This phenomenon can be explained in the following way. As the size of the diaphragm increases, it transmits the radiation concentrated in the side maxima of the intensity distribution, whose values (in the case that the adaptation process is not completed) are comparable with that of the central maximum. A photodetector measures the total power that passed through the diaphragm. The control algorithm tends to maximize this power. Because of the interference causing non-zero intensity of radiation near the diaphragm edges, this power can be much higher than the power in the case of exact focusing of the beams, although, simultaneously, the intensity at the central part of the diaphragm in this case is much lower. For the parameters of the beams used in the numerical experiment, the maximum radius of the diaphragm a, at which adaptation has the needed quality, is ≈ 0.02 mm.

Conclusion

In our study of the adaptive system for tilt corrections of the wave fronts of a multibeam laser, we have obtained the following results.

1. The equation has been derived for the focusing functional determining the quality of multibeam radiation of coaxial lasers operating at M-modes.

2. It has been found that the dependence of the focusing functional on the control variables is a nonmonotonic function, and therefore it is impossible to use a simple gradient method for adaptation.

3. The method of coverage, for which the Lipschitz constant is calculated with the allowance made for the specific parameters of the beams, can be used in seeking a global maximum of the focusing functional.

4. It has been found that the size of the diaphragm in the measuring channel significantly affects the efficiency of adaptation. At large diaphragms, the focusing functional in the process of adaptation can turn out to be much larger than unity, although the quality of radiation in this case is low.

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