The use of hybrid algorithm controlling bimorph mirror to focus light radiation

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The hybrid algorithm is offered for the adaptive optical system control in order to provide the optimal focusing of light field passing through the optical inhomogeneous medium. The presented method combines the advantages of classical optimization methods and genetic algorithms. The use of hybrid algorithm in solid-state multimode Nd:YAG laser allowed obtaining more than double improvement of the quality parameter M^2.

One of the methods for effective focusing of light radiation having passed through the optical inhomogeneous medium, is the use of the adaptive optical system of aperture sounding.[1] This system usually consists of a wave front corrector, electronic control unit, error signal sensor, and a software for determining the control voltages.

The method of aperture sensing is based on the algorithm of maximization of the parameter under control through introduction of trial perturbations into the phase profile of the light radiation. The controlled parameter can be presented either by peak intensity, or by a certain functional, depending on the radiation power getting into the aperture, of the set radius, or the combination of criteria.[2]

Individual elements of the corrector are controlled either by frequency variation or sequentially in time. The latter method was used in the given study, since it is stable, insensitive to noises, and quite simple in implementation, although it requires high time expenses.

To obtain the best radiation focusing, it is necessary to introduce a certain numerical characteristic as a criterion of the achieved result. On the one hand, the criterion should depend only on the measurable values and, on the other hand, reflect the purpose, for which the adaptation is introduced. Some estimation of the focusing quality criterion can be formulated in the form[3]:

$$J = \int r(x,y) I(x,y)\,\mathrm{d}x\mathrm{d}y, \qquad (1)$$

where $r(x, y)$ is the target region, where the radiation must be concentrated; $I(x, y)$ is the intensity distribution in the plane of the object focusing. The problem of control in the adaptive system is a search of a such a set of signals $\{U_1, U_2, ..., U_N\} = \{U_i\}$, at which the functional J [Eq. (1)] attains maximum, $i = 1, ..., N$, N is the number of channels for the corrector control; U_i is the voltage applied to the separate channel. As far as $r(x, y)$ and $I(x, y)$ depend on the beam phase distribution, the phase front, in its turn, is formed by the corrector and depends on voltages $\{U_i\}$, then $r = r(\{U_i\})$, $I = I(\{U_i\})$, and $J = J(\{U_i\})$, respectively.

Under actual conditions, J has several extrema. The search for a function extremum of many variables is a complex mathematical problem.[4] At present, a great number of optimization methods for functions of many variables have been developed and studied. The gradient methods[5] and genetic algorithms[6,7] are widely used for searching the extremum in the existing adaptive systems.

The iteration nature of the gradient algorithms good agrees with general operation principles of the adaptive optical system.[5] One of the most wide-spread methods connected with calculation of the gradient, is the method of the coordinate descent, where at each iteration, only one of the components changes. This method reduces the problem of the search for the function of some variables to the multiple solutions of one-dimensional optimization problems: at each step, J is considered at fixed values of all variables $\{U_i\}$, except for the jth variable. A proper choice of initial estimate is of great importance in the gradient methods.

The main difficulties in application of classical optimization methods to nonlinear functions are connected with the problems of local extrema, which are not the optimal solution and, therefore, do not lead to the best system adjustment. Attempts of solving the above-mentioned problems resulted in formation of the theory of genetic algorithms.[6, 7]

The genetic algorithm starts operation with a random set M of original solutions (chromosomes), which is called population. In terms of adaptive optics, a chromosome denotes a set of controlled voltages $\{U_i\}_j$, $j = 1, ..., M$. In course of iteration, the chromosome is estimated when using the correspondence function J.

New chromosome generation is formed either by hybridization of two parent-chromosomes from the current population or by the random change (mutation) with some probability of one chromosome. Mutations increase the time of algorithm convergence, but represent the high-power means for output from the local extremum. A new population is formed by a choice of chromosomes with greater J. After some iterations, the algorithm converges to the best $\{U_i\}$ which allows obtaining either an optimal solution, or that close to the optimal.

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The conducted investigations have shown that for searching the global extremum J when using the genetic algorithm, it is sufficient to form the population consisting no more than of a hundred sets of controlling signals $\{\{U_i\}_1, \{U_i\}_2, ..., \{U_i\}_{100}\}_k = \{\{U_i\}_j\}_k$, $j = 1, ..., 100$; k is the number of algorithm iteration. An increase in population leads only to increase in time of the algorithm convergence. Precise determination of the J maximum by the genetic algorithm, as a rule, takes much time owing to the stochasticity of operation principles.

At the first pass of the genetic algorithm, the values of $J(\{\{U_i\}_j\}_1)$ are equally spread over the field of possible solutions. After the second iteration, the majority of values $J(\{\{U_i\}_j\}_2)$ will be arranged in the region of J extrema. However, owing to mutations provided by the algorithm, after 3 or 4 cycles, more than 50% of population is found in the vicinity of a global extremum of J. Therefore, the genetic algorithm is applied only at the first stage for rough search of the global extremum, and then one of classical optimization methods is used, for instance, the method of the coordinate descent. Such a combination of methods, called the hybrid algorithm, would allow finding the best solution that is not guarantied by gradient methods; the convergence rate will appreciably decrease as compared to the genetic algorithm.[8]

In order to stop the genetic algorithm, one can use the following condition: if after some step, more than 50% of population satisfy the criterion $J(\{U_i\}_j) \in \{J_{\max} \pm \Delta\}$, one of $\{U_i\}$ can be used as initial estimate for the method of coordinate descent. Here Δ is a certain vicinity of $J_{\max}$, which is chosen starting from the current spread of J values.

The hybrid method of the corrector control was tested by us to improve the continuous radiation focusing of the solid-state multimode Nd:YAG laser in Singapore (DSO National Laboratories). The ceramic Nd:YAG rod was used as an active element with a diameter of 8 mm and a length of 140 mm. The advantage of ceramics as compared to single crystals is in possibility of making the large-sized active elements of high optical quality. Besides, radiating capacities of the ceramic active elements are close to those of the single-crystal.[9,10]

Pumping of the active element is carried out with five diode matrices, each of 1.5 kW power and $\lambda = 810$ nm. The thermolens appearing in the rod had a focal distance of 10 cm.

As a wave front corrector for radiation control, a bimorph deformable mirror with a passive cooling has been developed.[11] The mirror consisted of a silicon body and two piezoceramic disks bonded to it (Fig. 1*a*).

The first disk with solid electrodes served to change the general curvature of the mirror surface (Fig. 1*c*). A grid of 17 controlling electrodes in the form of sector parts (electrodes Nos. 22–18, Fig. 1*b*) was attached to the outer surface of the second piezodisk. These electrodes were used for reproduction of the wave front aberrations of the lowest order.[12] When applying the control voltage to the electrodes under the effect of reverse piezoeffect, the disk is contracted or expanded. This leads to the bending moment at the electrode boundary, which deforms the mirror's surface. A system of mirror control represents an electron block, which allows changing voltage on the electrodes in the range ±300 V. The mirror deformation amplitude was 8 μm. This mirror was meant for using both inside and outside the vibrator.

As a sensor of error signal in the adaptive system, the M2-sensor was used, carrying out the measurement of M^2, beam diameter, and peak intensity for determination of J and calculation of control voltages with application of the hybrid method. The M2-sensor consisted of a lens with $f = 500$ mm, a set of filters for beam attenuation, CCD-camera, and software.[13]

The experiment has been carried out with the laser made following the scheme "generator–amplifier" (Fig. 2).

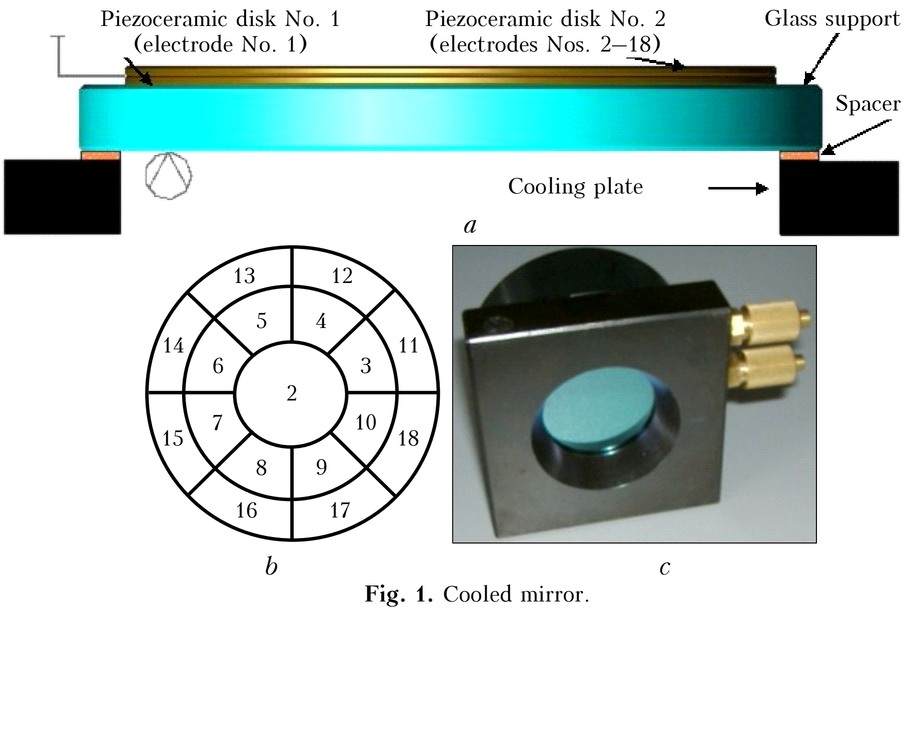

Fig. 1. Cooled mirror.

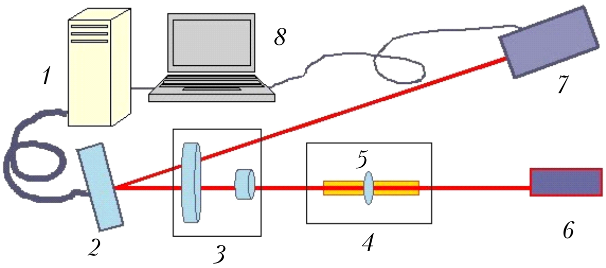

Fig. 2. Scheme of the experimental setup.

The single-mode diode laser *6* with power of 3 mW and $\lambda = 1.064$ μm served as a generator. The diode laser radiation *6*, passing through the active element of the Nd:YAG laser *4*, telescope *3*, was reflected from the adaptive mirror *2* and fell on the M2-sensor *7*. As far as the beam size inside the vibrator is traditionally small, the expanding 6-fold telescope *3* was used for matching the beam aperture and the bimorph mirror. Besides, the change in distance between the telescope lenses allowed compensating the thermolens *5*, appearing in the active element *4*. The control for mirror *2* was carried out owing to the computer *8* by means of the electron block *1*.

Figure 3*a* demonstrates the intensity distribution in the lens focus before pumping the active element, $M_x^2 = 1.6$ on the X-axis, and $M_y^2 = 1.7$ on the Y-axis. When pumping, M^2 increased up to $M_x^2 = 5.1$ and $M_y^2 = 6.5$ (Fig. 3*b*). The output power was equal to 10 W. After the closure of the feedback circuit due to the hybrid method, $M_x^2 = 2.6$ and $M_y^2 = 2.9$ (Fig. 3*c*).

a *b* *c*

Fig. 3. Intensity distribution in the far field: without pumping (*a*); with pumping without correction (*b*); with pumping after correction (*c*).

Results of the conducted investigations show a high efficiency of the hybrid method for the control of the adaptive optical system in order to improve the focusing of the light radiation passing through the optical inhomogeneous medium.

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