ISSN 1024-8560, Atmospheric and Oceanic Optics, 2018, Vol. 31, No. 3, pp. 238–242. © Pleiades Publishing, Ltd., 2018.
Original Russian Text © F.Yu. Kanev, N.A. Makenova, V.P. Lukin, O.L. Antipov, I.D. Veretekhin, 2018, published in Optika Atmosfery i Okeana.

Adaptive Correction of Thermal Distortions of Multichannel Laser Radiation

F. Yu. Kanev[a], N. A. Makenova[a,] *, V. P. Lukin[a], O. L. Antipov[b], and I. D. Veretekhin[c]

[a] *V.E. Zuev Institute of Atmospheric Optics, Siberian Branch, Russian Academy of Sciences, Tomsk, 634055 Russia*
[b] *Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, 603600 Russia*
[c] *Tomsk State University, Tomsk, 634050 Russia*
**e-mail: mna@iao.ru*

Received October 9, 2017

Abstract—Results of the simulation of multichannel radiation propagation under conditions of thermal blooming are presented. The correction of nonlinear thermal distortion by means of the beam phase and amplitude-phase control is considered. The results show the dependence of the correction effectiveness on the number of channels and on the precision of the reference beam phase retrieval. An additional increase in the effectiveness is possible by means of adjustment of amplification in the channels of the optical system, i.e., with the use of amplitude-phase control over the beam wavefront.

Keywords: adaptive optics, thermal blooming, multichannel radiation, phase conjugation, amplitude-phase control over the beam wavefront

DOI: 10.1134/S1024856018030077

INTRODUCTION

Multichannel laser systems are often used today for the transfer of energy by laser radiation. In these systems, individual beams are coherently combined at a focus object [1–5]. Each channel of such a system includes amplifiers and optical components that introduce an additional (to other beams) phase shift. This phase change can be implemented in electrooptical cells [3, 4], nonlinear and piezoelectric-crystal elements [1, 2], or with the use of other devices [6].

The interest of engineers and researchers in multichannel systems is a result of the maximal power of single-mode radiation being limited to nonlinear thermal phenomena which develop along an optical path, i.e., in the cavity active medium, in the atmosphere, at all beam-heated optical elements. The radiation power density and, hence, the probability of distortions can be decreased by an increase in the effective diameter of the source aperture due to beam splitting to several channels, which provide for the maximal intensity after coherent combination on the object.

In this relatively new branch of physical optics, a quite large amount of data is generated by numerical simulation [7–10]. It seems that the most comprehensive numerical study of multichannel beams propagating in a nondistorting medium and in a turbulent atmosphere has been performed in [7, 8], where the authors concluded from the simulation results that a close-packed multichannel (>30) system provides for the same power density on a focus object as a Gaussian beam of the corresponding diameter.

The effect of thermal distortions on the multichannel radiation quality and a possibility of increasing the power density on an object by means of focusing have been analyzed in [9, 10] by numerical methods. The authors have shown that thermal blooming in a multichannel system restricts the power transferred by a beam through the atmosphere. The adaptive control over the wavefront was not considered is these works.

Experimental methods for the study of multichannel systems are currently being actively developed. Further, work devoted to the practical possibility of correcting atmospheric distortions of radiation using adaptive optics algorithms [11] are of great interest.

The analysis of the literature shows that many practically important questions remain unsolved despite progress achieved in this field, for example, the problem of adaptive correction of thermal distortions in long atmospheric paths. The analysis of applicability of the amplitude-phase control to correction of distortions due to thermal blooming of radiation is also of interest.

1. MULTICHANNEL OPTICS MODEL

A scheme of a typical multichannel optics system [1, 3, 7, 9] is shown in Fig. 1. The feedback is looped by reference radiation; the radius is chosen larger or equal to the radiating aperture radius. This system is used for the simulation in our work. The adaptive correction is performed by introducing phase modulation

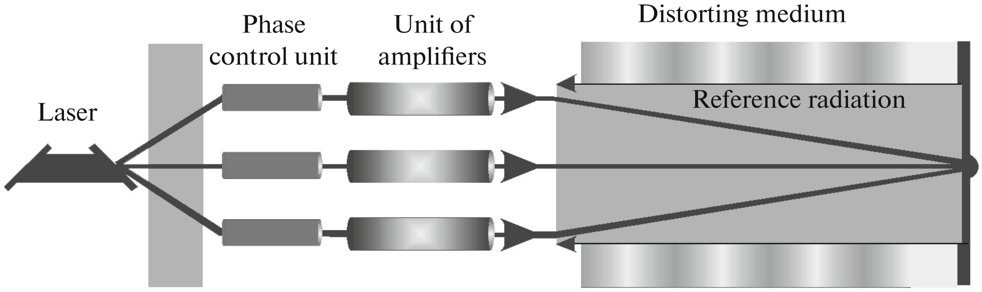

Fig. 1. Scheme of multichannel optics system with looped feedback.

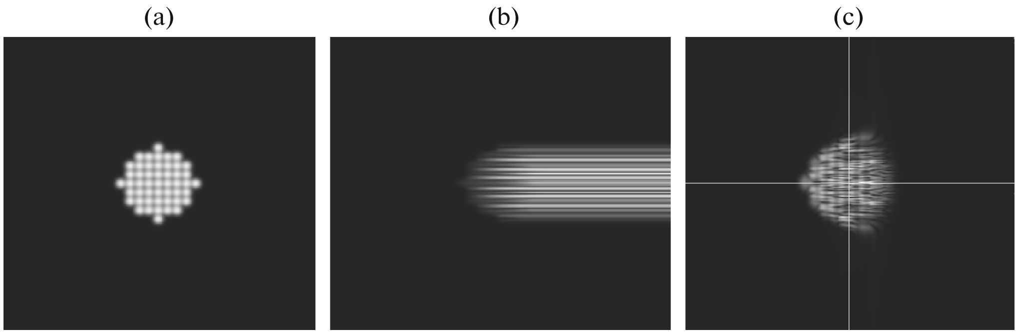

Fig. 2. Amplitude distribution of multichannel radiation (a) in the plane of radiating aperture and (b) on the focus object; (c) radiation-induced thermal lens.

in the channels (phase control) and by controlling the beam amplification (amplitude-phase control).

The radiation propagation through a nonlinear medium is described by the quasi-optics equation [12]:

$$2ik\frac{\partial E}{\partial z} = \Delta_\perp E + \frac{2k^2}{n_0}\frac{\partial n}{\partial T}TE,$$

where $E(x, y, z)$ is the complex field amplitude, the positive z coordinate is the radiation propagation direction, x and y are the coordinates on a transverse plane; $\Delta_\perp = \partial^2/\partial x^2 + \partial^2/\partial y^2$ is the Laplacian; k is the wavenumber; n_0 is the undisturbed refractive index; and T is the temperature of the medium. The path length was normalized to the diffraction length $Z_d = ka_0^2$, a_0 is the initial radius of the system subaperture.

The thermal blooming is considered by the introduction of the constitutive equation describing the heating of the atmosphere by a beam:

$$\frac{\partial T}{\partial t} + (V_\perp \nabla_\perp)T = \frac{\alpha I}{\rho C_\mathrm{p}}.$$

Here, $V_\perp$ is the flow speed of the medium transverse to the beam propagation path (scalar); t is the time; α is the absorption coefficient; I is the radiation intensity; and ρ is the medium density. Thermal distortions are characterized by the nonlinearity parameter

$$R_\mathrm{v} = \frac{2k^2 a_0^3 \alpha I_0}{n_0 \rho C_\mathrm{p} V_\perp}\frac{\partial n}{\partial T}$$

proportional to the beam intensity in the source aperture plane I_0 and the cubed initial beam radius a_0; and C_p is the specific heat at constant pressure.

The quasi-optics and constitutive equations are jointly solved based on the split-step algorithm [13], according to which the medium is represented as an array of phase screens and areas of free diffraction between them. The focusing criterion defined as

$$J(t) = \frac{1}{P_0}\iint \sigma(x, y) I(x, y, t)\,dxdy \qquad (1)$$

characterizes the field in the observation plane. Here, P_0 is the total radiation power; $\sigma(x, y)$ is the aperture function, equal to unity within the detector aperture and zero beyond it.

By introducing the normalization, an increase in the number of beams does not increase $J(t)$. It was expected that the inhomogeneous intensity distribution over an object could result in the dependence of the criterion $J(t)$ on the detector aperture size. Therefore, the criterion was calculated with apertures of different sizes.

2. EFFECT OF THERMAL DISTORTIONS ON THE QUALITY OF MULTICHANNEL RADIATION

Typical thermal distortions of multichannel radiation are shown in Fig. 2. The main feature of the thermal lens (Fig. 2b), as compared to the temperature

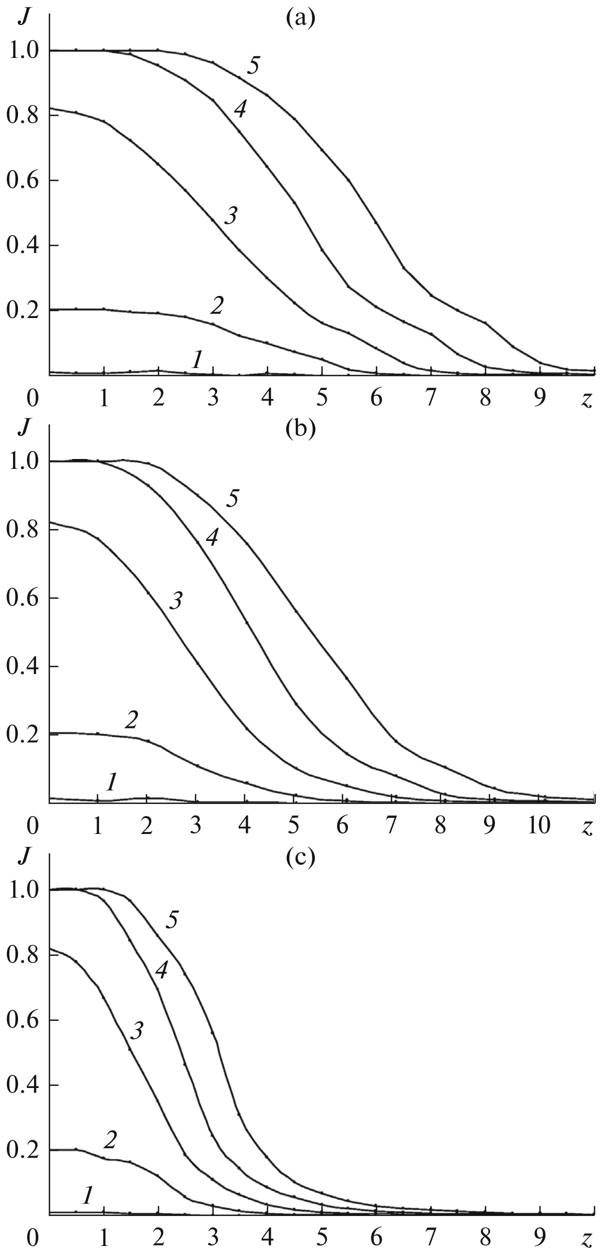

Fig. 3. The focusing criterion as a function of propagation distance of radiation recorded in an aperture with the radius equal to 1 (*1*), 5 (*2*), 10 (*3*), 15 (*4*), and 20 (*5*) initial radii of an elementary beam that forms the multichannel radiation; (a) $R_v = -5$, (b) -10, and (c) -15.

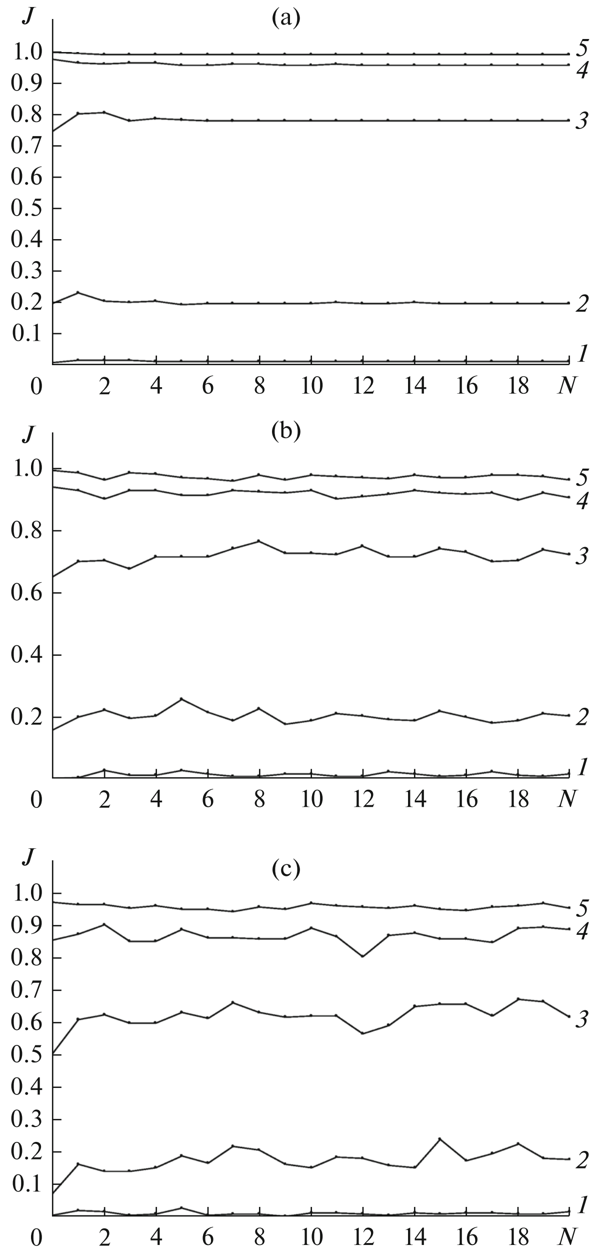

Fig. 4. Variations in the focusing criterion during the adaptive beam control based on the phase conjugation algorithm: (a) $R_v = -5$, (b) -10, and (c) -20; $z = 3$; N is the iteration number; curve numbers correspond to Fig. 3.

distribution characteristic for a Gaussian beam, is the small-scale structure, which results in a more irregular amplitude on the focus object.

The values of the focusing criterion (1) recorded in different cross sections of the propagation path at different values of the nonlinearity parameter R_v are shown in Fig. 3. One may note that the criterion decreases almost by an exponential law as the beam propagation distance increases; the criterion decreases with an increase in the modulus of R_v at short distances.

3. ADAPTIVE CONTROL OF RADIATION BASED ON A PHASE CONJUGATION ALGORITHM

The phase conjugation algorithm is used to correct thermal distortions. The correction results are illustrated in Fig. 4, where the variations in the criterion during the control are shown.

The nonlinearity parameter values correspond to a plane radiation phase profile at zero iteration (no con-

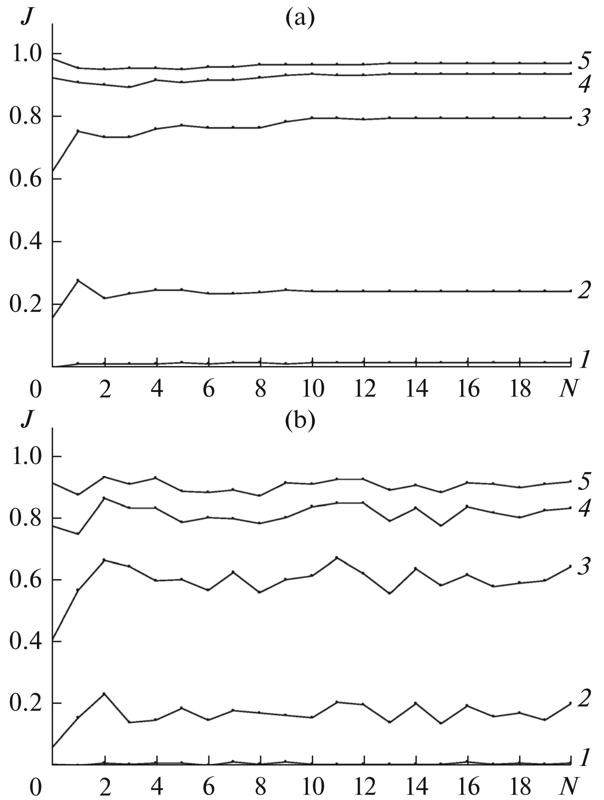

Fig. 5. Variations in the focusing criterion during the adaptive-phase control: (a) $R_v = -10$ and (b) -20; curve numbers correspond to Fig. 3.

trol). The plots show that the focusing criterion recorded within the detector apertures with the radii equal to 5 and 10 initial radii of an elementary beam increase during several first iterations at low power ($R_v = -5$) (Fig. 4a, curves *2* and *3*) and change little at any aperture radius. This means that the optical field concentration increases in the central region without focusing the beam as a whole. Increases in the power and, hence, in the modulus of the nonlinearity parameter result in undamped oscillations of the criterion (Figs. 4b and 4c) for the whole set of detector apertures selected. In general, one may conclude that the use of phase conjugation for the thermal blooming correction insignificantly increases the focusing criterion (if the radiation power is low) or does not change it.

4. AMPLITUDE-PHASE CONTROL OF THERMAL DISTORTIONS OF THE BEAM WAVEFRONT

An additional, as compared to the phase conjugation, increase in the optical field concentration on the focus object can be provided when changing to the amplitude-phase control of the radiation wavefront [14, 15]. The algorithm results are shown in Fig. 5. Thus, in a moderately nonlinear medium, the power density increases by about 30% in the central part of the beam (Fig. 5a, curves *2* and *3*). In contrast to the numerical experiment where the control was carried out based on phase conjugation, in the case considered the criterion oscillations are weak and rapidly damped.

An increase in the radiation intensity (Fig. 5b) results in the development of nondamping oscillations of the criterion, though it increases in the central part during the initial iterations.

CONCLUSIONS

The use of phase conjugation for control of thermal blooming of multichannel radiation is reasonable only at weak distortions ($R_v = -5$). The focusing criterion increases by about 10% in this case and only in the central part of the beam. An increase in the radiation intensity results in nondamping oscillations of the criterion.

The stability of the adaptive control can be improved when changing to the amplitude-phase control of the radiation wavefront. The algorithm provides for 30% growth of the criterion at the nonlinearity parameter $R_v = -10$. With a further increase in the power, undamped oscillations of the criterion also develop.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research (grant no. 16-45-700876).

REFERENCES

1. H. Bruesselbach, Sh. Wang, M. Minden, D. C. Jones, and M. Mangir, "Power-scalable phase-compensating fiber-array transceiver for laser communications through the atmosphere," J. Opt. Soc. Am., B **22** (2), 347–354 (2005).
2. A. A. Fotiadi, N. Zakharov, O. L. Antipov, and P. Megret, "All-fiber coherent combining of Er-doped amplifiers through refractive index control in Yb-doped fibers," Opt. Lett. **34** (22), 3574–3576 (2009).
3. T. Y. Fan, "Laser beam combining for high-power, high-radiance sources," IEEE J. Sel. Top. Quantum Electron. **11** (3), 567–572 (2005).
4. B. W. Grime, W. B. Roh, and Th. G. Alley, "Phasing of a two-channel continuous-wave master oscillator-power amplifier by use of a fiber phase-conjugate mirror," Opt. Lett. **30** (18), 2415–2417 (2005).
5. X. Fan, J. Liu, J. Liu, and J. Wu, "Experimental investigation of a seven-element hexagonal fiber coherent array," Chin. Opt. Lett. **8** (1), 48–51 (2010).
6. C. Bellanger, "Coherent fiber combining by digital holography," Opt. Lett. **33** (24), 2937–2939 (2008).
7. M. A. Vorontsov and S. I. Lachinova, "Laser beam projection with adaptive array of fiber collimators. I. Basic

consideration for analysis," J. Opt. Soc. Am., A **25** (8), 1949–1959 (2008).

8. M. A. Vorontsov and S. I. Lachinova, "Laser beam projection with adaptive array of fiber collimators. II. Analysis of atmospheric compensation efficiency," J. Opt. Soc. Am., A **25** (8), 1960–1973 (2008).
9. V. A. Banakh and A. V. Falits, "Assessment of multielement beam focusing under conditions of thermal blooming," Atmos. Ocean. Opt. **27** (3), 211–217 (2014).
10. V. A. Banakh and A. V. Falits, "Numerical simulation of combined beams propagation in the turbulent atmosphere in conditions of the thermal blooming," Opt. Atmos. Okeana **26** (5), 371–380 (2013).
11. T. Weyrauch, M. A. Vorontsov, G. W. Carhart, L. A. Beresnev, A. P. Rostov, E. E. Polnau, and J. J. Liu, "Experimental demonstration of coherent beam combining over a 7 km propagation path," Opt. Lett. **36** (22), 4455–4457 (2011).
12. M. A. Vorontsov and V. I. Shmal'gauzen, *Principles of Adaptive Optics* (Nauka, Moscow, 1985) [in Russian].
13. G. I. Marchuk, *Splitting Algorithms* (Nauka, Moscow, 1988 [in Russian].
14. F. Yu. Kanev, V. P. Lukin, N. A. Makenova, and E. I. Moisey, "New algorithm of formation of the required amplitude distribution under the phase control. Improving the efficiency of a two-mirror adaptive system," Atmos. Ocean. Opt. **21** (4), 321–326 (2008).
15. F. Yu. Kanev and V. P. Lukin, *Adaptive Optics. Numerical Simulation and Experiments* (Publishing House of IAO SB RAS, Tomsk, 2005) [in Russian].

Translated by O. Ponomareva