PACS numbers: 42.15.Fr; 42.25.Bs; 42.55.Rz; 42.70.Hj
DOI: 10.1070/QE2013v043n02ABEH015034

Conformal optical elements for correcting wavefront distortions in YAG : Nd^{3+} active elements*

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Abstract. **Correction of the wavefront is studied for the light beam passing wide-aperture YAG : Nd^{3+} single-crystal rods, which are used as active elements in high-power solid-state lasers. A nonideal character of the crystal structure is responsible for the deformation of the wavefront of passing radiation. By using the halftone technology we have developed conformal aberration correctors capable of compensating rod nonuniformities and reducing the laser radiation divergence by an order of magnitude. The results obtained make it possible to employ optically nonuniform active elements in laser constructions.**

Keywords: *laser active element, wavefront, correction of aberrations, conformal optical element, imitator.*

1. Introduction

Presently, high-power laser complexes are widely employed in telecommunication, materials processing, nuclear physics, and medicine. Crystal active elements made of YAG : Nd^{3+} are most often used for creating high-power lasers. Czochralski growing technology that was mastered by Russian industry provides production of cylindrical samples for optical-quality active elements with a dimension of up to 10 mm (the Strehl ratio of at least 0.9). Large-diameter samples are produced, however, with yet poor quality.

Wavefront distortions arising in light passing through optical elements result from a nonuniform distribution of the refraction index. Crystal active elements with large aperture have so high nonuniformity that can hardly be employed as a laser active medium.

The technology for obtaining such rods is rather cumbersome, time-consuming, and expensive. Yield of high-quality samples is very small. An important problem is to improve the rod quality. It can be solved by enhancing the technology of crystal growing, which is a difficult and science intensive process. However, there are various methods to compensate for aberrations of a wavefront in an active element for producing high-quality lasers. In unique scientific systems, such a correction is usually performed by means of adaptive optics [1 – 3], which is capable to dynamically correct and optimise the shape of a mirror for obtaining a minimal diameter of the focused laser beam. Such systems are very expensive and noticeably complicate the construction of a laser due to a necessity of employing a wavefront sensor.

Here we describe an employment of the static wavefront correctors [4, 5] for correcting crystal static aberrations. We call such correctors conformal optical elements, i.e., the optical elements with the transmission function that was chosen reasoning from specified external nonoptical conditions (for example, laser crystal imperfections) rather than from a set of standard optical surfaces. For example, the elements with a comparatively smooth transmission phase function were used for correcting aberrations of a HELEN laser amplifier [6]. However, the authors did not succeed in sufficiently effective compensating a wavefront deformation: the Strehl number was not greater than 0.2, whereas in an optically good system it should be at least 0.8. Correctors of wavefront distortions in laser crystals should withstand high power density, not degrade, be free of spectral distortions, compact, provide easy embedding into existing devices, have simple adjustment and service. Development of cost-effective technology of their production and application methods for a wide range of high-power laser systems is a rather actual problem.

Here we present the results of the application of a halftone raster technology for creating wide-aperture correctors of wavefront distortions basing on the phase maps that are characteristic for YAG : Nd^{3+} active elements with a diameter of 20 mm and length of 100 mm. Problems of their use in various operation conditions are also considered.

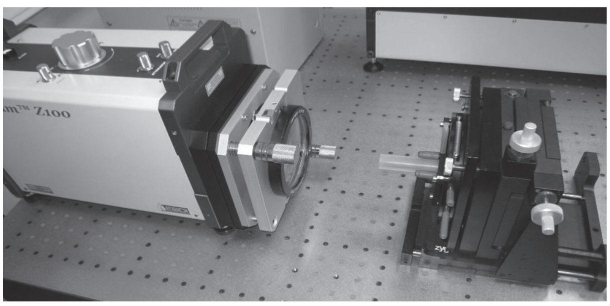

Figure 1. Measurements of a phase map of rod wavefront distortions by means of an interferometer.

*Reported at the 'Laser Optics' conference (St. Petersburg, Russia, June 2012).

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Received 24 October 2012; revision received 15 November 2012
Kvantovaya Elektronika **43** (2) 117 – 121 (2013)
Translated by N.A. Raspopov

2. Analysis of wavefront distortions

Phase distortions of a laser beam in active element crystals are measured by various interferometers [7, 8]. We performed the measurements by using an Intellium Z100 Fizeau interferometer [9] with the phase shift at the wavelength $\lambda = 633$ nm (Fig. 1). The standard test scheme was used with a plane reference wavefront and the root-mean-square deviation from flatness of at most $\lambda/20$. The measurement results for three rods are given in Fig. 2.

Since the refraction indices of fused silica used for producing the corrector at the wavelengths of 0.633 μm and 1.064 μm are almost equal the corrector may operate at both wavelengths.

At a first stage, a corrector for an unloaded rod was created. The fact is that a pump power induces thermal distortions of the refraction index in an active element, which deform the wavefront. The character of such distortions is mainly a so-called thermal lens. Principally, the corrector can correct a thermal lens as well; however, it is more convenient to introduce the particular compensating lens system, which is adjusted to eliminate the thermal lens effect after the laser onset.

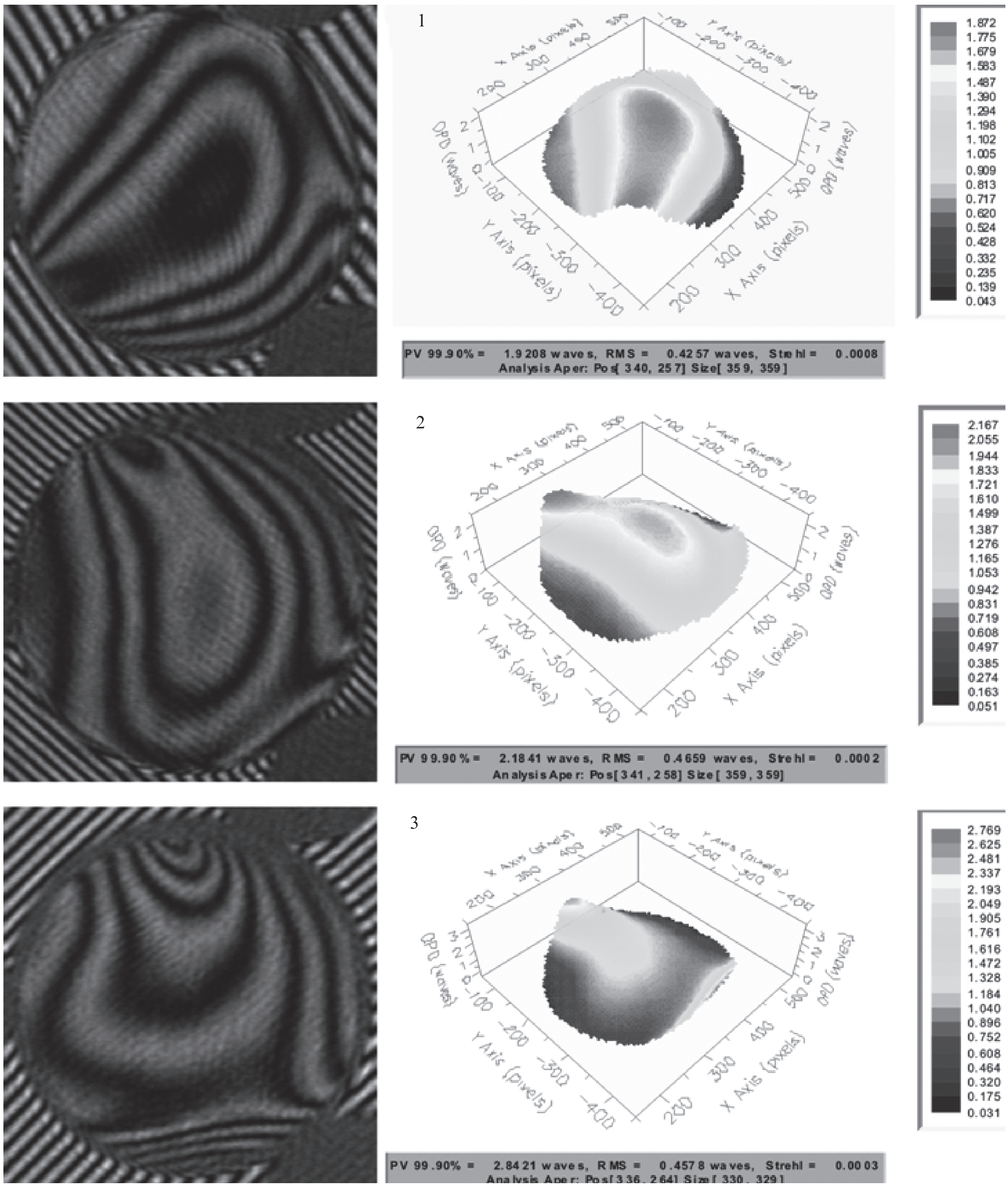

Figure 2. Interferograms (left) and the corresponding phase maps (right) of wavefront distortions for three rods.

3. Design and manufacturing of the conformal corrector and the diffractive imitator for rod distortions basing on phase maps

The phase maps measured were noisy and comprised many artefacts and high-frequency distortions. A correction of such distortions requires very accurate adjustment and is meaningless. This is why we have approximated the phase maps by Zernike polynomials. In this way, principal low-frequency errors may be compensated with a sufficiently large adjustment tolerance, which is important in practical applications. Then we encoded the phase function in a halftone photomask.

The method of creating a conformal corrector is based on the photoraster technology [10] first suggested for creating diffraction optics elements. We have adopted the method to contact photolithography with a gap. The desired light exposure distribution in a layer of an S1828 positive photoresist was formed by using a photomask placed at a distance of 0.4–0.5 mm from the photoresist surface. The photoresist was deposited on a fused silica substrate. After development in an alkaline solution the profile depth in the photoresist was almost proportional to the light exposure.

The halftone photomask was the amplitude diffraction structure formed in a chromium film by the direct laser writing [11] on a circular writing system CLWS-300IAE at the Institute of Automation and Electrometry, SB RAS. The structure comprised partially filled rectangular cells; it corresponded to the calculated exposure distribution. Thus, a totally filled elementary cell corresponded to a minimal transmittance and, hence, to a maximal microrelief height while using a positive photoresist as the shape-generating material. On the contrary, a completely empty cell corresponded to a maximal transmittance and maximal microrelief depth. A fragment of a rastered photomask structure is shown in Fig. 3.

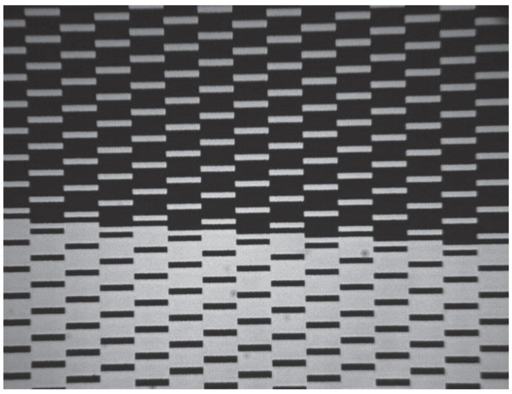

Figure 3. Microphotograph structure of a halftone photomask.

The minimal width of transparent and opaque cells was chosen equal to 1.5 mm in order to provide maximal reproducibility over the whole range of laser beam scanning rates in writing on the CLWS-300IAE circular writing system. To provide a wide dynamic range of exposure modulation we chose the cell dimension of 20 μm.

The halftone photomask was made on a standard photolithographic plate of size 127×127 mm covered by a chromium film. Masks for the rod correctors were placed at the centre of the plate. At a periphery, various test structures were made for enhancing the technology of microrelief formation. A group approach used in our technology provides simultaneous formation of more than 10 correctors for various crystals, which substantially reduces the corrector costs.

A microrelief is formed on the exposed photoresist after development and then it is transferred to a fused silica substrate by ion-plasma etching. The etching rates for fused silica and photoresist are approximately equal in the employed etching device of type Plasmalab 80 Plus. Hence, the profile depth in photoresist is chosen equal to that specified for fused fused silica. Finally, the corrector produced was actually the optical substrate one side of which had the shape compensating rod aberrations and the other was polished to the optical quality of $\lambda/20$.

Each corrector was surrounded by a test linear grating with a triangular groove profile and period of 1000 μm. The grating was used for controlling the profile depth and shape at all technological stages by means of an optical profilometer, namely, a white-light microinterferometer WLI [12]. A typical surface profile of a test grating is shown in Fig. 4. Employment of an Intellium Z100 laser interferometer with a phase shift is only appropriate for controlling ready correctors, whereas a destructive interference at the profile formation stage in the transparent film layer with the refraction index distinct from that of the substrate makes this device inappropriate. White-light interferometer is much less sensitive to light interference in the film due to incoherence of a wide-band source. Nevertheless, it only can control small structures.

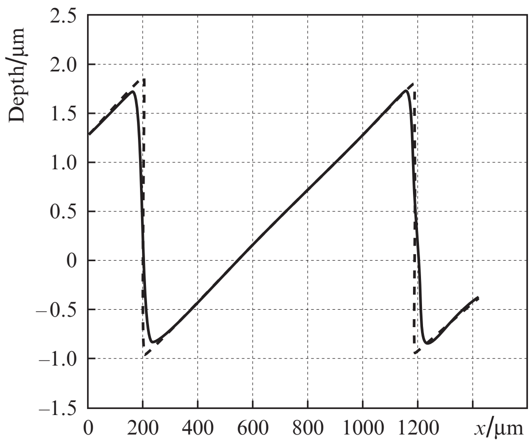

Figure 4. Calculated (dashed line) and measured (solid line) profiles of the test linear grating with the period of 1000 μm.

4. Creation of a imitator for active elements

Fabrication of a conformal element with a specified smooth profile is a complicated multistage technological process. At some stages, various errors occur: a nonlinearity of photoresist characteristics, nonuniform exposure, nonuniform development and etching and so on. In order to control the final surface shape without active element we have made a diffractive imitator of rod aberrations. By using such a imitator one can determine errors of a phase corrector fabricated and accordingly correct the halftone photomask (Fig. 5a) or

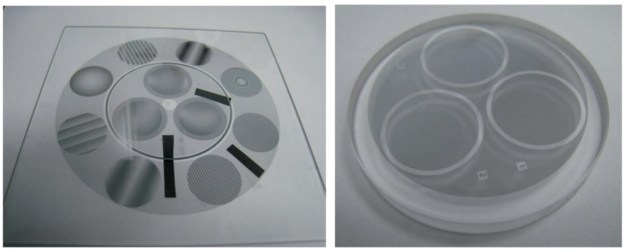

Figure 5. Photographs of the created halftone photomask (a) and diffractive imitator of rods (b).

change the technological process. The imitator allows one to test the corrector made if the corrected rod is unavailable.

The imitator is a linear amplitude diffractive grating, which has given distortions. The wavefront of the light beam reflected from the imitator and diffracted to a first order acquires distortions similar to those arose in light passing through the unloaded rod of the active element. The imitator inclination angle is 1°. A linear grating is disposed around the imitator. It returns light exactly back if the imitator is inclined at the angle of 1°. This is used for accurate adjustment of the imitator at a required angle. Imitators for three rods were created on a single substrate 60 mm in diameter (Fig. 5,b).

5. Experimental test of created conformal correctors and rod imitators

The correctors and imitators created were tested by means of an Intellium Z100 interferometer. The measuring scheme was similar to that used for rod test. At a first stage, the correspondence between the measured phase maps of diffractive imitators and rods under correction was verified. The correctors and imitators operate on different principles and are created by different technologies. The imitator was made as the amplitude reflecting diffractive element according to the binary technology, which provides the required accuracy of wavefront transformation. However, this technology is not suitable for corrector production due to poor diffraction efficiency of such elements. The corrector was made by a complicated multistage technology and operated in the transmission regime. Thus, the correspondence of the phase functions of these units ensured that the corrector was made without technological errors.

A collimated beam passed through the corrector, then reflected from the corresponding imitator and then passed again across the corrector. In this case, aberrations of the wavefront should be compensated at a proper relative position of the corrector and imitator. Separately measured interferograms for rod 1 imitator (Fig. 2) and the corresponding corrector are shown in Figs 6a and b. They are similar to the accuracy of a phase shift. The phase map in Fig. 6c shows the result of their joint operation after adjustment of their relative position. In Fig. 6d, the result of their joint operation is presented as the numerical simulation assuming lack of adjustment errors. In the latter case, the peak amplitude of distortions reduces twice. The numerical simulation testifies that at the wavelength of 633 nm the wavefront error may reach $\lambda/40$, which is much better than required.

The correctors were also tested with the active element in RFYaTs-VNIITF by using a Shack–Hartmann sensor at the

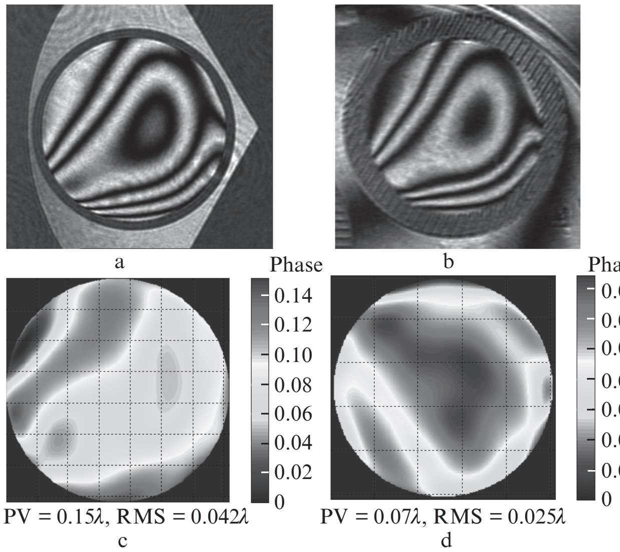

Figure 6. Interferograms of a imitator (a) and wavefront corrector (b), a phase map of the corrector with a imitator (c), the difference of imitator and corrector phase maps (d).

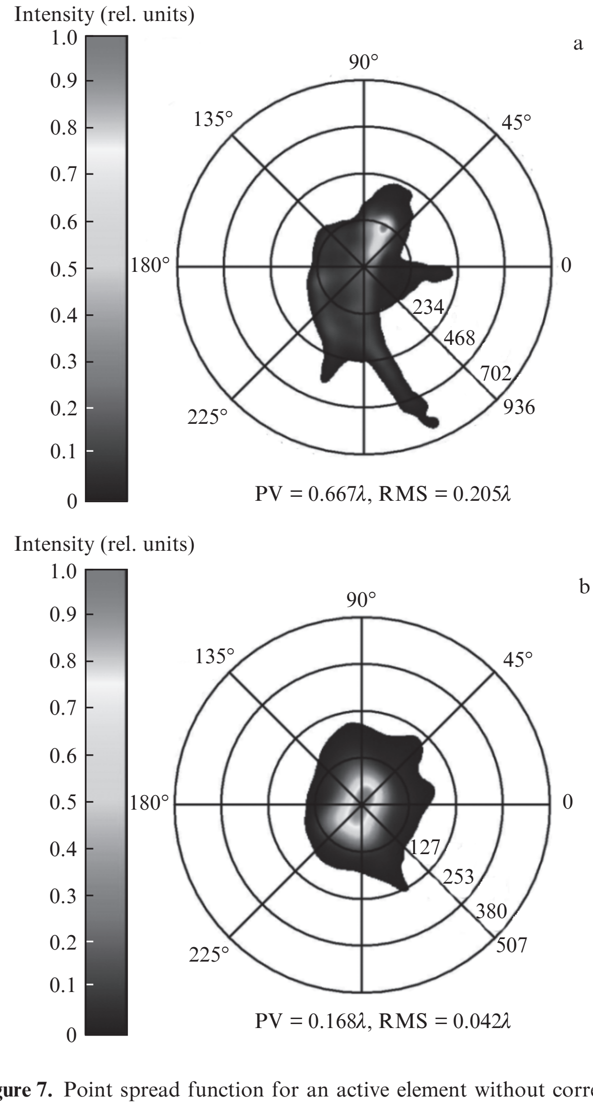

Figure 7. Point spread function for an active element without correction (a) and after correction (b) in polar coordinates (the polar radius value is given in microns).

operation wavelength. The scheme was adjusted in such a way that distortions of the wavefront were minimal at a maintained light aperture.

The test results (Fig. 7) revealed that after correction, the wavefront error for all active elements reduced to 0.042 μm rms and lower, that is, to $\sim\lambda/15$. Issuing from Marechal criterion for small wave aberrations we find that the Strehl number is less than 0.93. Tests of the operating laser system with a conformal corrector show that the beam divergence fall by a factor of 10 [13].

The radiation resistance of the created correctors was also experimentally determined. Under the action of the pulsed laser radiation with the wavelength of 1.064 μm and duration of 4 ns it was at least 17 J cm^{-2}.

6. Conclusions

Methods used presently for correcting and improving the beam quality of high-power solid-state lasers (phase conjugation, adaptive optics, spatial filtering) are sufficiently effective; however, they lead to greater mass/dimension parameters, complicated construction of lasers, lower reliability and efficiency. The alternate method for correcting wavefront distortions that combines an utmost brightness of radiation and high laser efficiency is employment of conformal optical elements. Advantages of such elements are simple maintenance, minimal mass/dimension parameters, and minimal losses if antireflection coatings are used.

For testing the conformal correctors we have measured phase maps of the YAG : Nd^{3+} active elements with the diameter of 20 mm and length of 100 mm. Based on the measurement results we calculated and created the correcting elements. Then joint experimental tests of element capabilities were performed to correct distortions of the wavefront in conditions similar to those in which the phase maps had been obtained. It was found that rms of the wavefront after correction was at most $\lambda/20$ for a 80% aperture.

The production technology used allows one to create correctors with the profile depth of up to 3–4 μm at the light beam diameter of at least 20 mm. Radiation resistance tests showed that the damage threshold for the correctors is above 17 J cm^{-2} at the wavelength of 1.064 μm and pulse duration of 4 ns. The divergence of output laser radiation with a conformal corrector was reduced by a factor of 10 [13].

Acknowledgements. The work was partially supported by the Interdisciplinary Integration Project No. 112 of Siberian Branch of Russian Academy of Science, Project 24-8 of the Program for Fundamental Research of Presidium of Russian Academy of Science, and the Russian Foundation for Basic Research (Grant Nos 12-02-00974-a and 12-02-01118-a).

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