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Wide-aperture bimorph mirrors and the problem of the „print-through“ structure of the separated piezoplates

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The results of a study on the occurrence and compensation of the „print-through“ effect on piezoceramic plates in wide-aperture bimorph mirrors of a combined type are presented. It is shown that the use of the technique of „training“ the piezoelectric plates by applying control voltages to the electrodes according to a special algorithm can significantly improve the initial flatness of the corrector. This allows to apply this type of flexible mirror in high-power laser systems, including those designed for laser fusion.

Keywords: deformable mirror, bimorph electrode, piezoceramic actuator.

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Modern laser systems designed for research into the interaction of ultra-strong electromagnetic fields with matter and, ultimately, for controlled laser thermonuclear fusion require high-power optical elements and light beams with transverse dimensions of tens of centimeters. Such systems are subject to large-scale aberrations [1,2]. This is precisely why bimorph controlled mirrors are used in most systems of this kind [3,4]. One distinctive feature of this type of correctors is the possibility to form and compensate for low-order aberrations of the wave front of light radiation with the use of a fairly limited number of control elements (electrodes). This is due to the modal nature of deformation of the surface of a bimorph mirror, which is induced as a result of application of control voltages to a separate electrode or group of electrodes. Flexible mirrors of this kind reproduce very efficiently traditional low-order optical aberrations (defocusing, astigmatism, coma, spherical aberration, etc.), which are mainly typical for the radiation of modern pulsed lasers. Bimorph correctors are distinguished by large ratios of the diameter of a mirror to its thickness, which may be as high as 40 to 1. This makes it difficult to both polish the glass substrate and mount and secure the mirror in a frame. The solutions to these problems have already been discussed in our studies [5–7]. However, there is another problem, which, as it turns out, is specific to wide-aperture bimorph mirrors: the so-called print-through of piezoceramic plates. This effect is typical for stacked-actuator deformable mirrors (including membrane

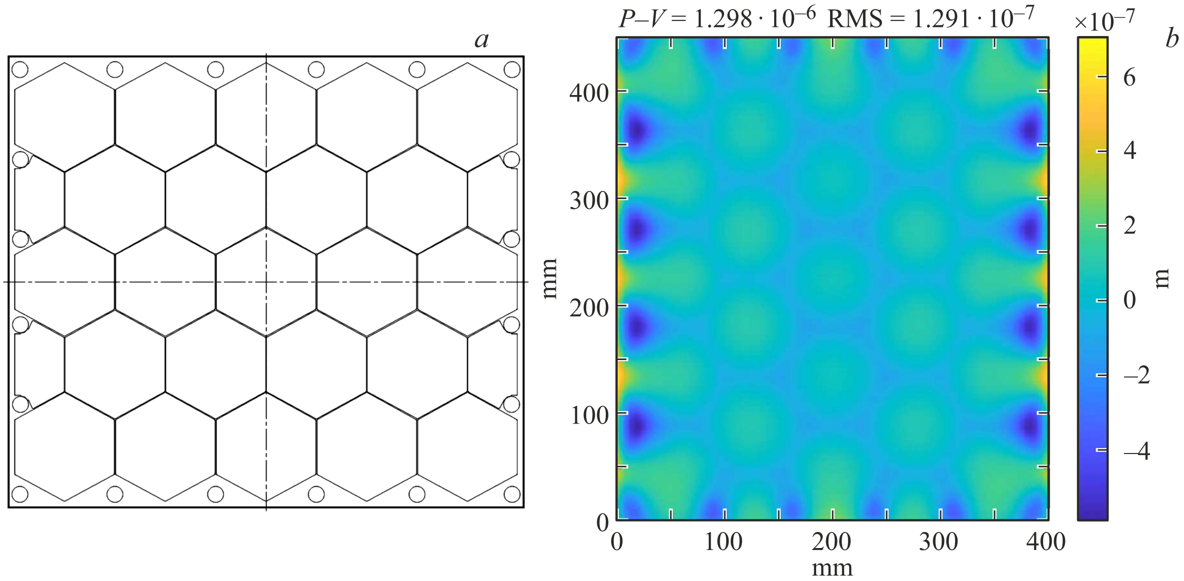


Figure 1. Diagram of arrangement of hexagonal piezoelectric plates on the reverse surface of a glass substrate (*a*) and results of modeling of mirror surface deformation upon heating by 50 °C (to a temperature of 70 °C) (*b*). The maximum nonflatness of the surface ($P-V$) is 1.3 μm; the corresponding RMS deviation from plane is 129 nm.

correctors [8,9]): a parasitic periodic structure replicates the arrangement of control actuators and is somewhat similar to a diffraction grating, and forms on their reflective surface. When radiation is focused, this effect makes it impossible to obtain a fine focal spot close to the diffraction one [10]. Small-aperture bimorph mirrors (up to 240 mm in diameter) are devoid of this effect simply because they do not have any optomechanical inhomogeneities and use two or three solid and homogeneous elements glued together: a relatively thick (up to 5 mm) glass substrate and thin piezoceramic plates (up to 0.7 mm). There are no additional elements that may „pull“ or further deform the reflective mirror plate at the interface of „zones of influence“ of the electrodes. The only real aberration observable in this case is defocus which is caused by the large diameter-to-thickness ratio of the entire structure (gravity also plays a role here). However, almost all modern laser systems require the use of wave front correctors with an aperture of 600 mm or more. Current process technologies limit the size of thin piezoceramic disks to 220–240 mm. Therefore, if a wide-aperture bimorph wave front corrector needs to be fabricated, one is forced to use a mosaic piezoceramics arrangement and a set of separate plates glued to a passive substrate (Fig. 1, *a*) instead of a single plate.

We have already presented the results of examination of a wide-aperture flexible mirror of the so-called combined type (a bimorph rectangular corrector was secured along the periphery to separate controlled piezoceramic actuators) in [11]. The initial flatness of this corrector was $1.5\,\mu$m, and the effect of print-through of bimorph piezoelectric plates was not observed. The process of fabrication of such flexible mirrors involves gluing thin piezoceramic disks to a glass substrate and final optical polishing of the bimorph plate $(P-V)$ a residual amplitude error no greater than $1\,\mu$m. This is followed by low-temperature (up to 80 °C technological preparation of the polished substrate for sputtering, the actual process of deposition of a reflective coating, and rigid mounting of the entire structure on piezoelectric pusher actuators. The mirror surface is strongly deformed after the dielectric coating deposition; rather significant local deformations stand out against the background of general curvature and astigmatism (up to $30-40\,\mu$m). The structure of separately glued piezoceramic hexagonal plates starts to manifest itself. As was demonstrated in computer modeling of deformation of the mirror surface at various stages of the process chain, the effect of print-through of individual piezoelectric plates should already be observed upon heating of the bimorph structure (Fig. 1, *b*).

The amplitude of induced surface deformations depends on temperature, and the RMS deviation from plane is on the order of 100–150 nm for a 50 °C mirror heating. The adhesive bond between the piezoceramics and the glass substrate was neglected in calculations. However, experiments reveal that the presence of glue and the change in its properties upon heating are precisely the factors that lead to residual mirror surface deformation errors and the emergence of print-through after cooling of the structure. The modeling results also demonstrated that such temperature deformations of the surface cannot be compensated by applying corresponding control voltages to the electrodes of the piezoelectric plate, since the response functions of the electrodes of the bimorph mirror are modal in nature.

We have fabricated series of bimorph correctors 468×410 mm in size with a mosaic structure of piezoelectric plates in accordance with the procedure described above. The typical surface profile of one of these mirrors after final smoothing is shown in Fig. 2, *a*. The surface nonflatness was on the order of $1\,\mu$m $(P-V)$ or $0.15\,\mu$m (RMS deviation) after the subtraction of defocus and astigmatism. Local surface deformations associated with the positioning of individual piezoelectric plates were not observed. A multilayer reflective dielectric coating was applied to these mirrors. The process temperature was monitored closely at all deposition stages, and the maximum heating of the mirror substrate did not exceed 70 °C. Following sputtering, a general curvature of the mirror surface with a significant

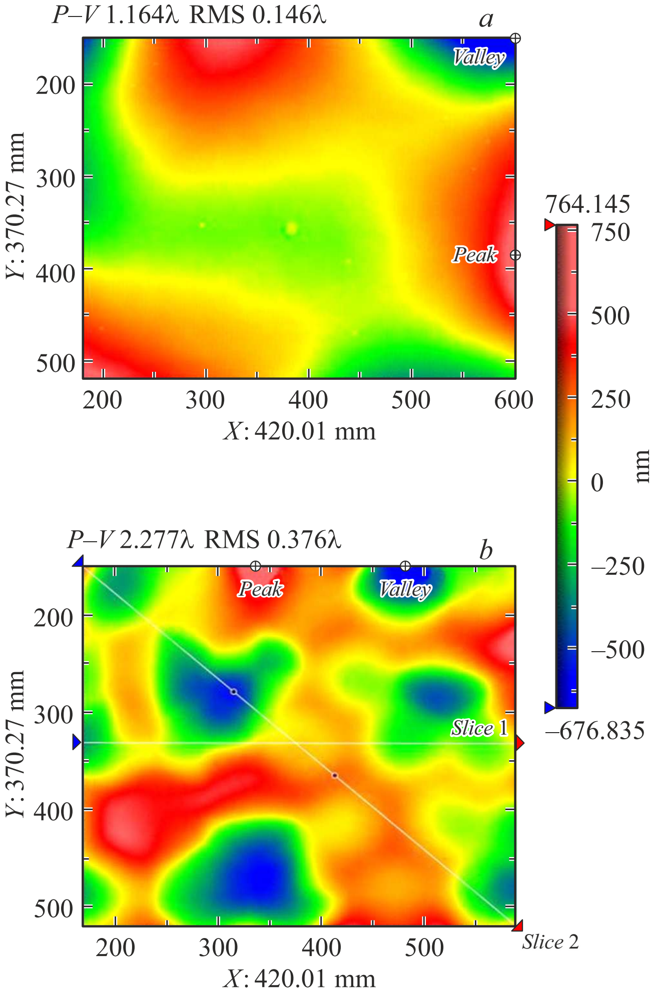
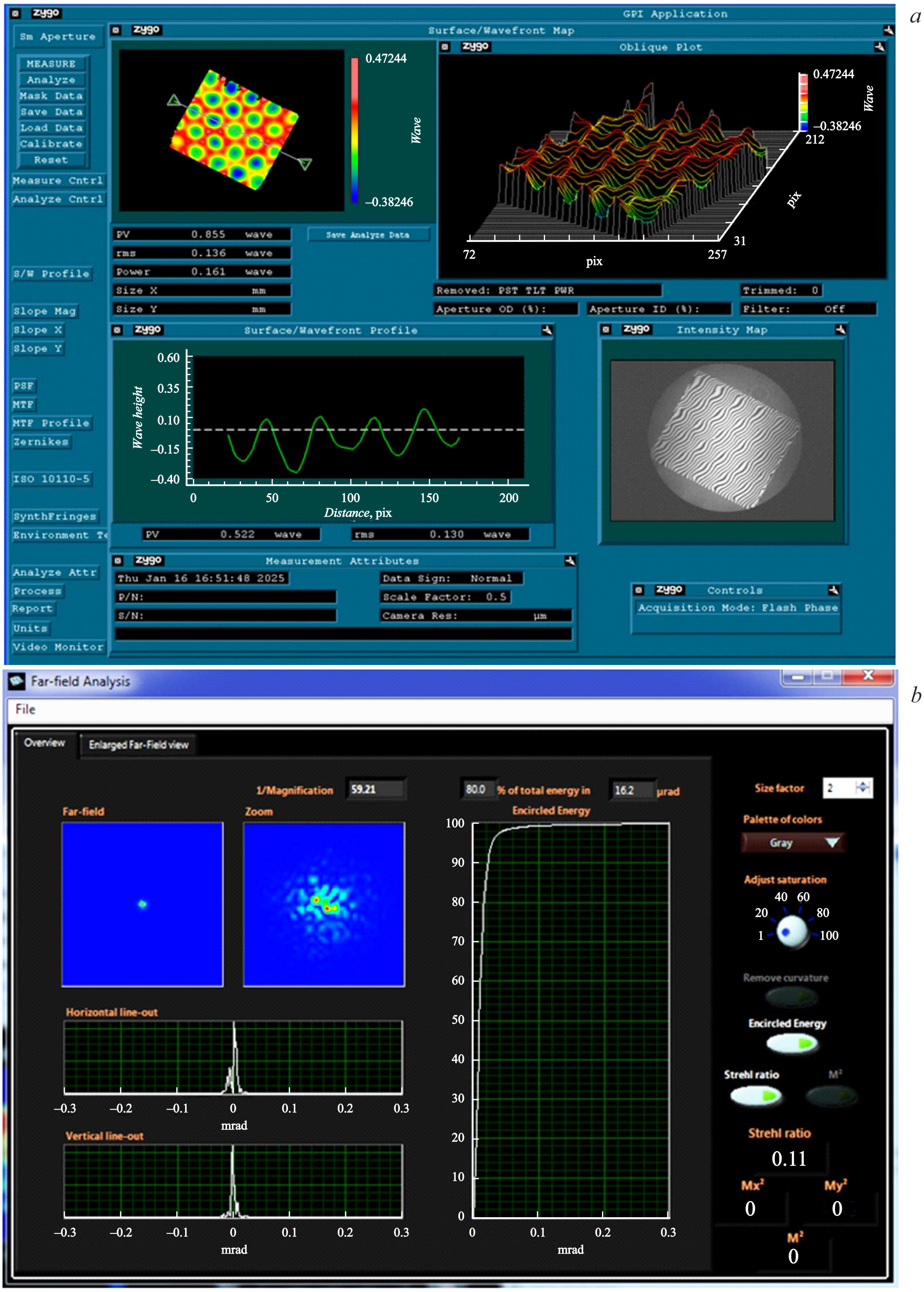


Figure 2. Surface profile of the bimorph plate after polishing (*a*) and print-through of the piezoelectric plate grid after deposition of a dielectric coating (the RMS deviation is 380 nm) (*b*).



PV 0.855 wave
rms 0.136 wave
Power 0.161 wave
Size X mm
Size Y mm
Removed: PST TLT PWR
Trimmed: 0
Aperture OD (%):
Aperture ID (%):
Filter: Off
PV 0.522 wave
rms 0.130 wave
Thu Jan 16 16:51:48 2025
P/N:
S/N:
Data Sign: Normal
Scale Factor: 0.5
Camera Res: μm
Acquisition Mode: Flash Phase

1/Magnification 59.21
80.0 % of total energy in 16.2 μrad
Size factor 2
Palette of colors Gray
Strehl ratio 0.11
Mx^2 0
My^2 0
M^2 0

Figure 3. Shape of the mirror surface after mounting in the frame and adjustment by peripheral piezoelectric actuators (the RMS deviation is 136 nm) (*a*) and experimentally measured intensity distribution of a super-Gaussian laser beam after reflection from the adaptive mirror at the focus of the lens (*b*).

amplitude was observed. When it was subtracted, the grid of glued piezoelectric plates was manifested clearly (Fig. 2, *b*), indicating residual deformation of the surface associated with heating of the bimorph corrector.

The cell amplitude varies from 50 to 800 nm. Internal mechanical stresses in multilayer dielectric coatings relax by approximately 2/3 within about a month. When a mirror substrate is mounted on piezoelectric actuators, additional deformations are introduced. However, they are compensated fairly easily by the same peripheral piezoelectric actuators. This makes it possible to obtain an almost flat surface of a deformable mirror with an $P-V$ amplitude of the order of $1.5\,\mu$m. However, the problem of print-through of individual piezoelectric plates remains.

It should be noted here immediately that any inhomogeneities or residual stresses both inside (e. g., striae) and outside (local inhomogeneities) the polished planes of optical elements always lead to residual errors. There is only one question: how accurately will the resulting polished surface profile correspond to the required one? According to Maréchal's criterion, an optical system may be considered ideal if the total RMS aberrations in it do not exceed 1/14 of the wavelength of light radiation [12]. The deformable mirrors fabricated in this study are designed for use in a laser system with a wavelength of $1.053\,\mu$m; i. e., in terms of laser radiation focusing on the target, the deviation of the formed wave front from the ideal one should not exceed 70–75 nm (RMS). The residual error arising as a result of print-through of the grid of piezoelectric plates of the bimorph mirror (136 nm) is almost 2 times higher than the permissible one (Fig. 3, *a*).

When this mirror was installed in an actual optical circuit, the focal spot formed after reflection from it had a shape far from the diffraction one; the profile of the flexible mirror surface (Fig. 3, *a*) corresponded to the intensity distribution in the focusing plane is shown in Fig. 3, *b*. The Strehl factor was 0.11, which is definitely far from the required value of > 0.8.

We propose to use the method of adaptive mirror training to solve the problem of smoothing out residual aberrations. Since the corrector surface after polishing had no significant local distortions, it should have returned to its original state in the process of relaxation after sputtering and heating. Induced mechanical stresses should relax. To speed up this process, we placed the mirror in a 24″ Fizeau interferometer (Zygo Corporation, CT, United States) and applied randomly various sets of control voltages ranging from -100 to $+200$ V. The voltages themselves were applied sparingly with a „soft" step of 1–3 V and with „freezing" at the end point for a certain time or a wave-like change in the states of piezoelectric plates relative to each other. Following tens of thousands of such iterations (training took up to ten days for each mirror), the mirror surface was corrected successfully: the residual aberrations were reduced to the required levels (Fig. 4, *a*). Their amplitude was $0.53\,\mu$m, and the RMS value was 52 nm. These mirror parameters provided an opportunity to obtain a calculated Strehl factor of 0.85. Figure 4, *b* shows the intensity distribution in the focal plane of the focusing lens corresponding to the discussed mirror profile. More than 80 % of intensity are concentrated in the diffraction-limited region.

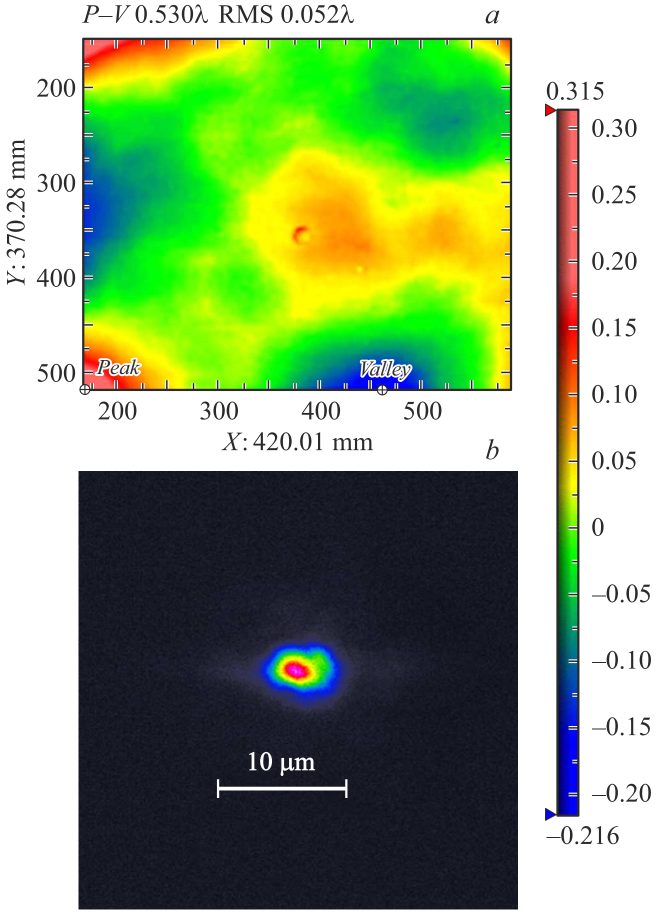


Figure 4. Surface profile of the combined bimorph mirror after the training process (the RMS deviation is 52 nm) (*a*) and intensity distribution in the focal plane of the focusing lens (*b*).

We note in conclusion that bimorph wave front correctors have one characteristic feature: the longer they are operated in aberration correction systems, the more effective they become and the better their target surface becomes. This is attributable primarily to the very large diameter-to-thickness ratio and the resulting issues of temporary variations of the mirror surface parameters.

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Conflict of interest

The authors declare that they have no conflict of interest.

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