Piezostack deformable mirror with high technological effectiveness

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Abstract. Deformable mirror (DM) is an active element that can change the shape of the surface to compensate for wavefront aberrations. Historically, the development of DMs started from piezostack deformable mirrors (PDM) due to their large stroke, flexibility in actuators geometry, high resonant frequency. However, the cost of PDMs is comparatively high because of their labor-intensive process of manufacturing. In the article innovative design of PDM is presented. The assembling of unconventional PDMs was carried out using piezoceramic combs. This step should allow to decrease number of technological steps, increase spatial resolution of the mirror and thereby reduce the cost of final product.

1. Introduction
Adaptive optics as branch of science was founded in 1953 by H. Babcock [1] for astronomical task to nullify the influence of wavefront aberrations on the image resolution. During evolution of adaptive optics element base the using of the adaptive optical systems (AOS) dramatically grew\textsuperscript{[2]-[5]}. Currently, the areas of exploitation of DMs as actuating unit are high-power laser applications [6],[7], biological imaging [8],[9], free-space communication [10],[11]. Any AOS includes three main elements: control unit, wavefront sensor and wavefront corrector (mainly presented by DMs). The scheme of the traditional AOS is shown in Figure 1.

Number of different technologies could be used to modify the shape of mirror surface: piezoelectric [12],[13], electrostatic [14], electromagnetic [15]. The piezoelectric DMs in turn could be divided on two large categories: bimorph [16] and piezostack [17]. The most popular type of the mirrors for correction of low- and high-order aberrations is PDM due to its flexibility to customer demands in geometry of actuators, adapting pitch and stroke of the mirror. Moreover, high stiffness of the mirror allows to polish the optical surface of the mirror after assembling, such technological step significantly decreases initial aberrations of the DM.

Despite large number of advantages PDMs have a few shortcomings such as comparatively high cost, labor-intensive process of manufacturing, large risk of failure of control elements during assembling [18]. To avoid the influence of these effects we propose to produce PDMs from piezoceramic combs. In section 2 the main view, design features of traditional piezostack deformable mirror will be given. Section 3 presents the conception of the developed PDM with the main steps of producing the
control elements (piezocombs). In section 4 will be represented the main characteristics of the PDM such as response functions of the mirror, amplitude-frequency response and stroke. Section 5 will summarize all paragraphs with final conclusions, also ways of modernization of such mirror design will be briefly provided.

![Image](image.png)

**Figure 1.** Scheme of conventional adaptive optical system.

### 2. Conventional piezostack deformable mirror

Manufacturing process of the conventional PDM contains four main steps such as: 1) gluing the actuators on the rigid base; 2) gluing the passive substrate made of silicon, copper or glass to the other side of the piezoactuators; 3) providing electric connection and 4) finally, placing coating with high reflectivity (not less than 99.8%). The scheme of the traditional PDM is presented in Figure 2. In such case the shape of the substrate is modifying due to pushing (pulling) the rear side of the mirror substrate because of changing initial thickness of piezoactuators by applying control voltage to them. The value of the length change $\Delta l$ is proportional to the electric field intensity $\xi$, the length of the piezostack $l_0$ and piezoelectric coefficient ($d_{33}$)\[19\]: $\Delta l = d_{33} \xi l_0$. This leads to the deformation of the reflecting substrate in the place of the location of the piezostack.

![Image](image.png)

**Figure 2.** Scheme of conventional stacked-actuator deformable mirror.
3. Conception of the piezostack deformable mirror with rigid design

One of the most important criteria of using one kind or another of DMs is the cost of the device. Therefore, we propose to manufacture PDMs from multilayer piezoceramic combs. It will allow to get scalable wavefront correctors and decrease the risk of failure of control elements during assembling process. In Figure 3 the concept of such DM is presented.

![Figure 3. Concept of PDM with rigid design.](image)

First of all, it should be explained the procedure of development of main components – piezocombs and rigid basement. The whole process of manufacturing contains 12 steps and is shown in Figure 4. As a producing material we used PZT-based ceramic due to its high sensitivity to applied voltage, a high Curie point and high electromechanical coupling coefficient [20].

We produced a few piezocombs with length 24 mm and thickness 4 mm. On each comb 5 actuators with size 4*4 mm are placed. The main view of developed piezocombs with wiring to them are shown in Figure 5. By combining on the rigid base made of piezoceramic material such combs we can assemble PDM with desirable configuration of actuators. In our case we chose the net of 10*10 actuators, however such concept of assembling allows to get almost any aperture of the mirror. On the next step the thin mirror substrate was glued on the top of the actuators. The aperture of such mirror was 50x50 mm and it included the matrix of 10x10 actuators. The thickness of the mirror substrate made of optical glass was 1 mm. Such ratio between the thickness of the substrate and its aperture allows to get reasonable stroke of the mirror and good initial quality of the surface.

![Figure 4. Scheme of producing main deformable components – piezocombs and rigid basement.](image)
Figure 5. Piezoelectric combs with individual multilayer actuators and electric connection.

4. Parameters of the developed piezostack deformable mirror

To investigate key parameters of the developed PDM we used optical diagnostic setup, which presents traditional AOS [21] (Figure 6). As a wavefront analyzer we exploited Shack-Hartmann wavefront sensor [22].

Figure 6. Optical diagnostic setup for investigation of mirror parameters. 1. Tracer laser; 2. Diagnostic laser; 3. Diaphragm; 4. Collimating lens; 5. Piezostack deformable mirror; 6. Input lens of the telescope; 7. Output lens of the telescope; 8. Shack-Hartmann wavefront sensor; 9. Personal computer with software; 10. Control unit.

After that we measured response functions of the developed mirror (Figure 7). By applying voltages with value 100 V per one actuator the maximal local deformation (stroke) of such a wavefront corrector can be calculated. The deflection of the mirror at 100 V was equal 1.35 µ, so stroke of the mirror is close to 5 microns. Also, the first resonant frequency of the mirror was measured (Figure 8). The procedure of the measuring is considered in previous work [23]. It was equal to 7.6 kHz. It means that such mirror can operate in closed-loop regime of the adaptive optical system with speed about 800 Hz.
5. Conclusion
The PDM with rigid design made of piezoceramic combs was manufactured and investigated. The square arrangement was chosen with 10*10 pcs matrix on it. The maximal stroke was given about 5 microns (1.35 per 100 V). The voltage range for such mirror is in the range from -50 to +300 V. The first resonant frequency was found at 7.6 kHz and will allow to use this PDM in fast AOS with operational speed up to 800 Hz.

In the future we are going to produce such PDMs from monolithic piezoceramic block. The upper part will contain many piezoceramic plate layers with conducting electrodes in-between and the lower part is a thick solid piezoceramic material serving as a base to support the matrix of multilayer piezoceramic stacks. Then such monolithic block will be sawn on individual piezoactuators.

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