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Studying the Electrophysical and Mechanical Parameters of Piezoceramic Materials for Deformable Cartridge-Type Mirrors

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Abstract—The authors consider electrophysical and mechanical parameters of piezoceramic materials based on lead zirconate titanate. The data show that modules with multilayer actuators with cross-sectional areas of 4 × 4 mm, nominal displacements of up to 4.3 μm, and element capacitances of 12 nF are designed to create cartridge-type deformable mirrors.

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INTRODUCTION

The numerous fields of application of wavefront correctors predetermines the need to improve the characteristics of existing devices or develop new ones to compensate for distortions of laser radiation. There is also a trend toward the development of reliable and miniature correctors with high density of control elements [1, 2]. There are various technical and technological ways of improving the spatial resolution of wavefront corrector actuators: etching, lithography, chemical and physical deposition [3], the use of liquid crystal (LC) elements [4], laser engraving, and split electrode welding [5]. Similar technologies are used to create deformable MEMS mirrors [6], LC light modulators [7], or bimorph wavefront correctors [8, 9]. Nevertheless, there is an increase in the density of control elements when designing flexible mirrors of the piezoelectric actuator type [10], due to the problem of developing reliable piezoelectric elements based on materials with a high piezoelectric modulus to obtain the necessary local deformation of the reflecting surface.

This work considers the possibility of developming new materials based on lead zirconate–titanate with improved electrophysical and mechanical properties in order to create deformable mirrors of the piezoelectric actuator type.

ELECTROPHYSICAL AND MECHANICAL PARAMETERS OF FERROELECTRIC MATERIALS WITH A DIFFUSE PHASE TRANSITION

Due to their high electro-physical properties (piezoceramic coefficients d_{31}, d_{33}), solid solutions based on lead zirconate titanate (LZT) are used as the material for developing control elements when fabricating piezoelectric deformable mirrors [13]. However, there is still a need to develop materials with the ability to precisely adjust the parameters of piezoceramics. LZT ceramics is a unique ferroelectric system where diffuse phase transitions can be obtained in order to enlarge the morphotropic region [14]. Such systems are called ferroelectric relaxors [15]. A similar effect can be achieved by doping an LZT system with combined additives of lead magnoniobate, which is in turn a prominent ferroelectric relaxor [16], and barium–strontium titanate. It was established in [17] that the unique properties of relaxors are due to the formation and growth of nanoregions (nanodomains) in a crystal because of disorder in the environment of different ions located in crystallographically equivalent positions.

Material PKP-12 was fabricated on the basis of zirconate–titanate with the doping of lead magnoniobate and barium strontium titanate to study its electrophysical and mechanical properties and establish the similarity of the behavior of the developed material with ferroelectric relaxors.

To determine the main parameters of the material, a number of samples were fabricated using conventional ceramic technology. Silver electrodes were deposited on the surfaces of all developed samples, except for elements with longitudinal polarization, by burning-in a silver-containing paste. The samples were polarized in air by applying an electric field of 8 kV/cm for 10 min at 120°C, followed by direct natural cooling to room temperature.

To obtain samples with longitudinal polarization, each sintered block was subdivided into separate ele-

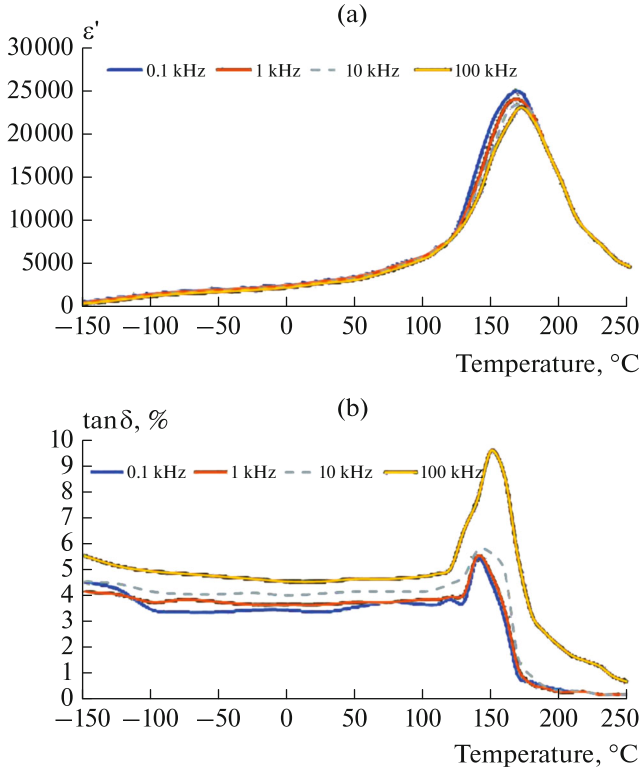

Fig. 1. Frequency of (a) relative dielectric permeability ε'(*T*) and (b) dielectric loss tangent tanδ(*T*) of the considered non-polarized composition as a function of temperature.

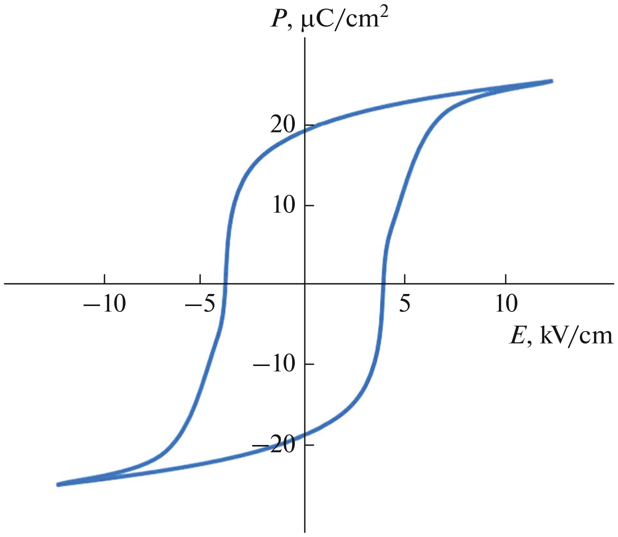

Fig. 2. Dielectric hysteresis loop of our PKP-12 material.

ments with electrodes deposited via chemical deposition [18].

Dynamic means of measuring were used to investigate the main electromechanical properties of the material: relative dielectric permeabilities $\varepsilon_{33}^{T}/\varepsilon^{0}$ and $\varepsilon_{11}^{T}/\varepsilon^{0}$; dielectric loss tangent tanδ; coefficients of electromechanical coupling k_p, k_{15}, k_{33}, k_{31}, k_t; piezoelectric moduli d_{31}, d_{33}, d_{15}; speeds of sound V_1^{E}, V_4^{D}, V_3^{D}; mechanical quality Q_m; Poisson ratio δp; and density ρ.

A WK 6510B precision impedance meter (Wayne Kerr Electronics) was used to determine the electrical capacitance, resonance frequency, and antiresonance of polarized piezoceramic samples.

Figure 1 presents the frequency of relative permeability ($\varepsilon' = \varepsilon/\varepsilon_0$, where ε is the permeability of the material) and tanδ of unpolarized ceramics at 0.1, 1, 10, and 100 kHz as a function of temperature.

In the considered range of frequencies, a local shift of T_m is clearly seen as the frequency changes (Fig. 1a), a distinctive characteristic of ferroelectric relaxors. A dispersion effect (the splitting of curves at different frequencies) is also observed at a temperature considerably lower than T_m. Maximum dispersion is observed around 130°C. It is also worth noting that the tanδ(*T*) maximum is asymmetric (Fig. 1b), another distinctive feature of ferroelectric materials with a diffuse phase transition [19].

The behavior of the resulting material's polarization was also studied, depending on the applied external field. Figure 2 shows the material's dielectric hysteresis loop, from which we determined the value of the coercive field: $E_c \approx 4$ kV/cm. The hysteresis loop is saturated and close in shape to those characteristic of ferroelectric soft ceramics.

The electrophysical characteristics of this composition were then measured under normal conditions ($T = 20 \pm 5$°C). The measured data are summarized in Table 1. They show the investigated material had high values of dielectric permeability, piezoelectric moduli, and coefficients of electromechanical coupling, allowing this material to be used in manufacturing devices for actuator engineering.

FABRICATING PIEZOCERAMIC MODULES WITH MULTILAYER ACTUATORS FOR CARTRIDGE-TYPE DEFORMABLE MIRRORS

Multilayer modules with five separate control elements were manufactured on the basis of our experimental data on piezoelectric materials. The fabrication of multielement piezoceramic actuators is illustrated in Fig. 3 and consists of several steps:

The charge (mixture of initial materials) of piezoceramic material PKP-12 was first prepared from metal oxides using classical ceramic technology. The material was synthesized through a solid phase reaction by

Table 1. Electrophysical properties of the studied material

Parameter	Unit of measurement	Value
T_c	°C	160
$\varepsilon_{33}^{T}/\varepsilon_0$ (1 kHz)	–	4950
$\varepsilon_{11}^{T}/\varepsilon_0$ (1 kHz)	–	4400
$\tan\delta$ (1 kHz)	%	1.5
k_P	–	0.66
k_{15}	–	0.71
k_{33}	–	0.70
k_{31}	–	0.38
kt	–	0.53
$\lvert d_{31}\rvert$	10^{-12} C/N	325
d_{33}	10^{-12} C/N	660
d_{15}	10^{-12} C/N	940
V_1^E	10^3 m/s	2770
V_4^D	10^3 m/s	2470
V_3^D	10^3 m/s	3700
Q_m	–	60
δp	–	0.34
ρ	kg/m^3	7400

firing the charge in a muffle furnace at 850°C. The resulting charge was then ground to powder and pelletized (1).

The granular PKP-12 material was then pressed into blocks that were subsequently dried in a desiccator and fired at 1230°C inside a muffle furnace (2). The sintered blocks were ground on all sides and sawn into base elements 5 mm thick (3) and active layers 0.5 mm thick (4).

The active piezoelectric layers were coated with a silver-based paste that was burned in by smooth annealing at temperatures up to 700°C. Finally, a portion of the silver coating was removed to separate tracks (5).

Table 2. Main parameters of fabricated piezoceramic modules

Parameter	Value
Capacitance of one actuator in a module, C_{rated}	11–12 nF
Dielectric loss tangent $\tan\delta$, no higher than	0.015
Displacement at a control voltage of 300 V	4.1–4.3 μm

The prepared 26 × 26 × 26 × 5.5 mm base elements were assembled into a package with active layers (26 × 26 × 0.5 mm) and subsequent compression welding of the piezoceramic block (6). The assembled and welded block was again subjected to mechanical processing (the grinding of end surfaces) (7), after which it was sawed into individual modules (8).

The cut parts of the block were then sawn into individual actuators such that the active layers were separated from each other by a gap of 1 mm, but remained rigidly fixed to the base element (9).

Each actuator of the resulting module was coated with a layer of burned-in silver-based paste in order to switch the electrodes of active layers. A 0.4 mm thick MGTF wire was then soldered to each current lead (Fig. 4). Finally, the piezoceramic was polarized and the characteristics of the individual actuators in the module were measured. The obtained values are summarized in Table 2.

CONCLUSIONS

Similar and distinguishing features in the behavior of the electrical properties of PKP-12 piezoceramic material were established. It was shown that in terms of elastic properties, this material is very close to the relaxor ferroelectrics and has great pliability in a wide range of temperatures. The resulting material also had a high longitudinal piezoceramic coefficient of 660 pC/N and a low dielectric loss tangent of no more than 1.5%.

Piezoceramic modules with 5 multilayer actuators 4 × 4 × 15 mm in size were fabricated on the basis of our study of the electrical and mechanical parameters of the obtained materials. The capacitance of each actuator was 12 nF. The maximum displacement at a control voltage of 300 V lay in the range of 4.1–4.3 μm.

The developed piezoelectric elements will be used to create a cartridge-type deformable mirror with the possibility of obtaining the required configuration of control elements by combining our piezoceramic modules.

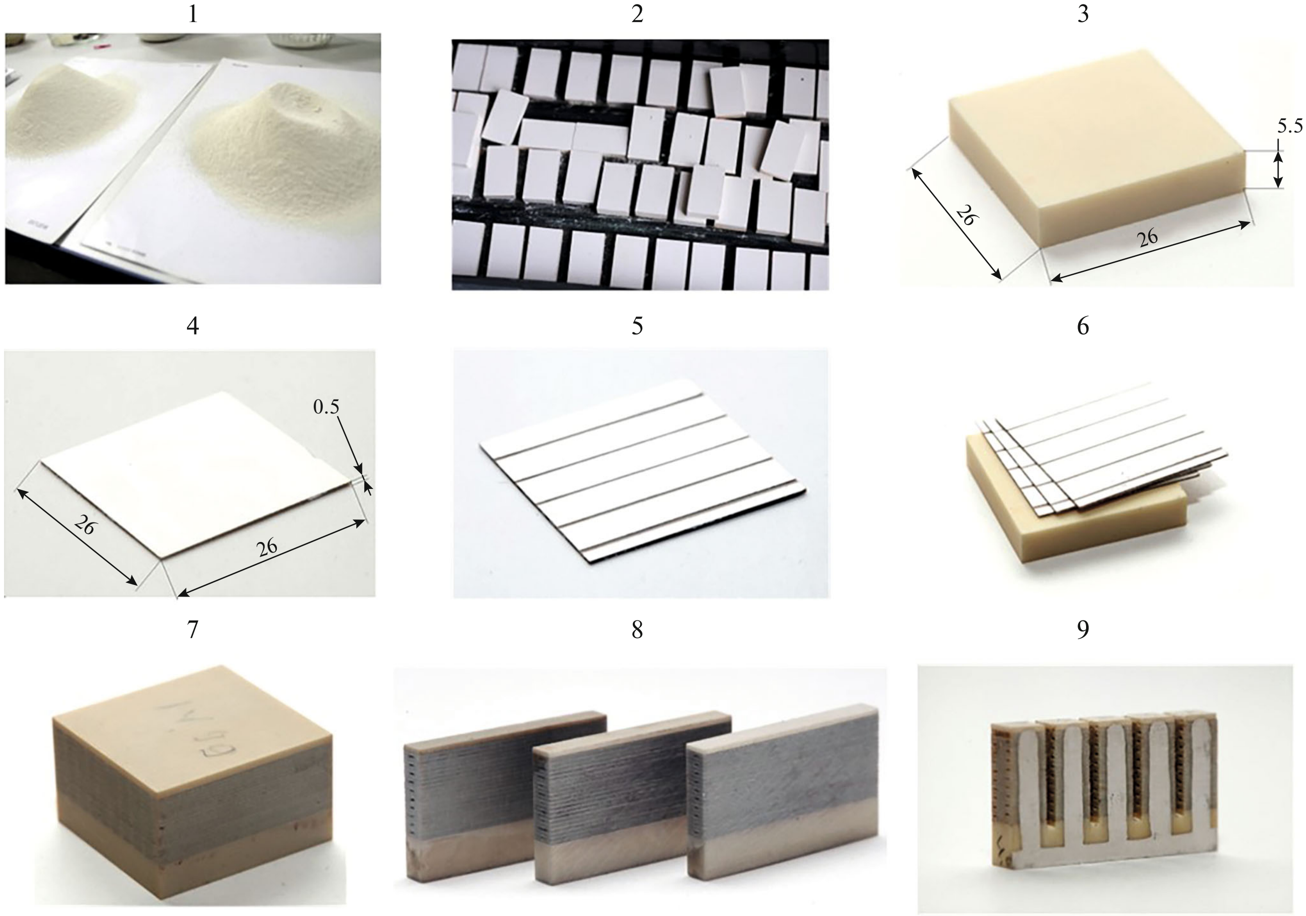

Fig. 3. Layout of piezoceramic modules for a cartridge-type deformable mirror.

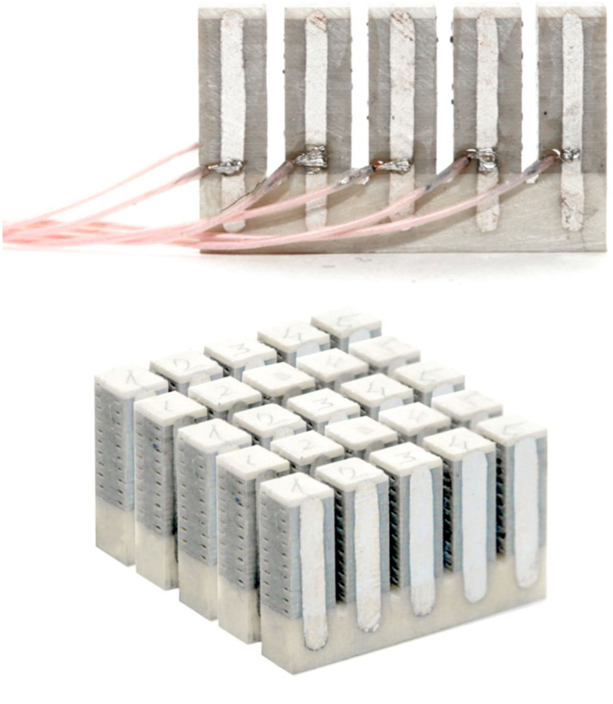

Fig. 4. General view of fabricated piezoceramic modules with switched wires for applying control voltages.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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