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Application of PMN-32PT piezoelectric crystals for novel air-coupled ultrasonic transducers

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Abstract

Due to very high piezoelectric properties of PMN-PT crystals they may significantly improve performance of air-coupled ultrasonic transducers. For these purpose vibrations of PMN-PT rectangular plates and strips were investigated. An air-coupled ultrasonic transducer and array consisting of 8 single piezoelectric strips were designed. Operation of the transducer was simulated by the finite element method using ANSYS Mechanical APDL Product Launcher software. Spatial distributions of displacements inside piezoelectric elements and matching strip were obtained. Experimental investigations were carried out by the laser Doppler vibrometer Polytec OFV-5000 and the Bruel&Kjaer microphone 4138 with the measurement amplifier NEXUS WH 3219. It was found that performance of the ultrasonic transducer with PMN–32PT crystals was a few times better than of a PZT based ultrasonic transducer.

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Keywords: Air – coupled, Ultrasonic transducers, PMN-32PT, Displacements;

1. Introduction

Lead magnesium niobate-lead titanate [PbMg1/3Nb2/3O3-PbTiO3 (PMN-PT)] single crystals have excellent piezoelectric properties, what enables to exploit them in air-coupled ultrasonic transducers with enhanced performance. Objective of this research was development and experimental verification of novel effective air-coupled ultrasonic transducers with PMN-32PT piezoelectric crystals. For air - coupled applications the operation frequency usually is $f \leqslant 100$ kHz [1]. In order to obtain such low frequencies the main transverse length mode of PMN - 32% PT crystals of <011> cut and [011] poling directions has been selected (Fig. 1.a). For this purpose rectangular PMN-32PT single crystals with dimensions (15 x 5 x 1) mm^3 were investigated. Anisotropic, elastic and

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piezoelectric properties in direction 1 and 2 are different [2]. The direction 2 gives a greater electromechanical coupling coefficient (k_{32} up to 0.97), therefore it was selected. For matching of acoustic impedances of piezoelectric elements and air various matching elements were investigated. From the measured resonance f_r and antiresonance f_a frequencies the electromechanical coupling coefficients k_{32} were calculated by [3].

2. Investigation of the PMN-PT piezoelectric elements

In order to estimate spatial distribution of normal displacements of the PMN - 32PT crystal elements measurements by the laser vibrometer POLYTEC OFV - 5000 were carried out. The eight piezoelectric crystal strips with dimensions (15 x 5 x 1) mm^3 were measured. During measurements the electric excitation voltage was U=1V. To get a better understanding of spatial distributions of mechanical displacements a numerical modelling of vibrations at the fundamental resonance frequencies has been performed. Operation of the transducer was simulated by the finite element method using ANSYS Mechanical APDL Product Launcher software. A single piezoelectric strip was modelled by SOLID5 elements taking into account complete piezoelectric e_{ij}, elastic c_{ij} and dielectrics ε_{ij} matrixes of the PMN-PT crystal [4]. The piezoelectric element is anisotropic, which has eight nodes with four nodal degrees of freedom including three displacements in the x, y and z directions and electric voltage. It was assumed that the strip surfaces are coated by electrodes to which a harmonic excitation voltage U=1V is applied. The modelling takes into account free boundary conditions and coupling between electric and mechanic fields. Efficiency of the electromechanical transformation was estimated by the coefficients k_1 and k_2:

$$k_1 = \frac{\zeta_1}{U}, \qquad k_2 = \frac{\zeta_2}{U}, \tag{1}$$

where k_1 is the transformation coefficient in direction 1 and k_2 - in direction 2, ξ_1 is the mechanical displacement of the strip edge in direction 1 and ξ_2 - in direction 2, U is the applied voltage.

Measurement results along two perpendicular edges of the plate (15 x 15 x 1) mm^3 are presented in (Fig. 1.b). The frequency responses of the single piezoelectric strip (Fig. 2a) and the piezoelectric element with the matching strip (Fig. 2b) are shown in Fig. 3 and Fig. 4.

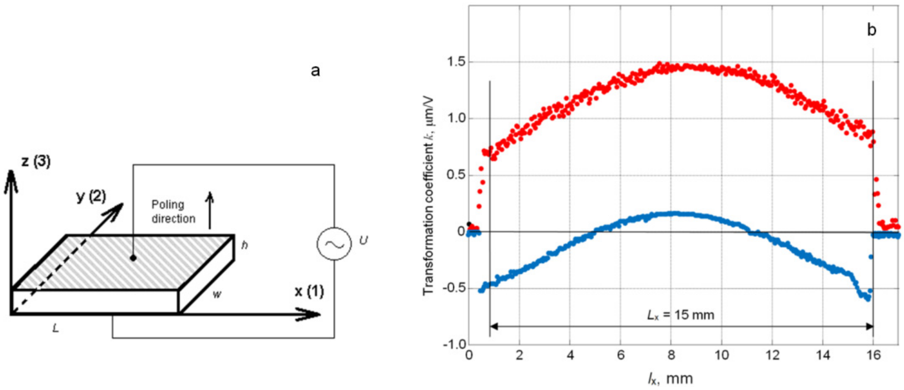

Fig. 1. (a) geometry of the piezoelectric plate; (b) measured electro-mechanical transformation coefficients: k_2 at f_{r2}=37.2 kHz red, k_1 at f_{r1}=68.1 kHz – blue colour.

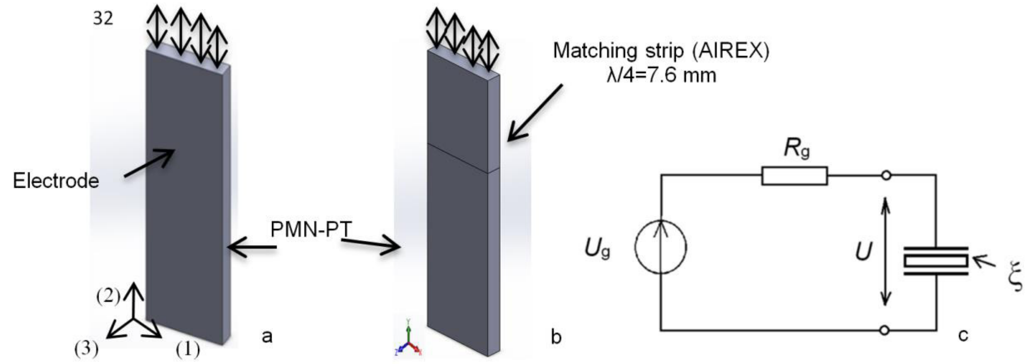

Fig. 2. (a) the single element; (b) the single element with the matching strip; (c) electric circuit.

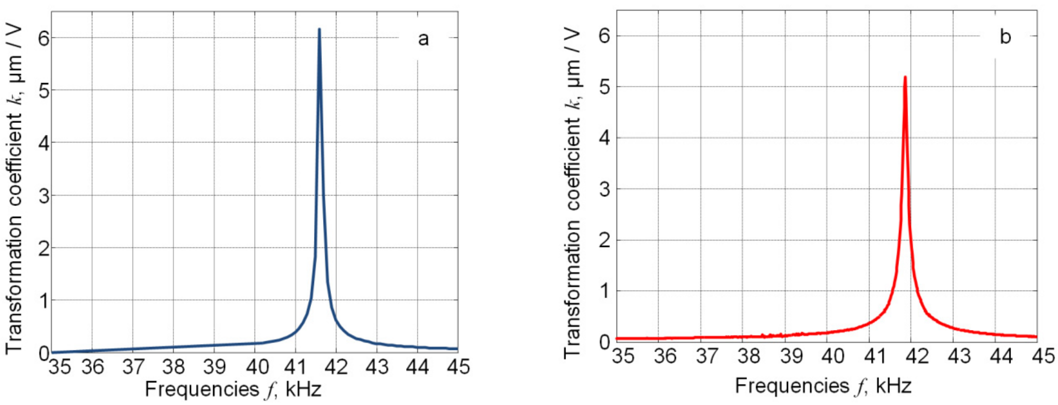

Fig. 3. Frequency responses of the single element: (a) simulated by FEM; (b) measured by the laser interferometer.

The matching strip was made of the polystyrene foam (AIREX R90.200). The length of the matching strip is λ/4, where λ is the wavelength of the ultrasonic wave in the layer at the operation frequency of the array [5-6]. As it was mentioned above as an active radiating surface the edge of the PMN-PT crystal strips perpendicular to the direction 2 gives is exploited. Frequency responses in air of the single piezoelectric strip (Fig. 2a) and the piezoelectric element with the matching strip (Fig. 2b) are presented in (Fig. 5a) and (Fig. 5b) respectively. The measurements were performed at the distance 1mm from the radiating surface. Measurements were carried out using the measurement setup, which consists of the ultrasonic measurement system "ULTRALAB" (Ultrasound Research Institute) with XYZ scanner, the electric generator Hewlet - Packard 33120A and the 4138 type acoustic microphone with the measurement amplifier NEXUS WH 3219 (Bruel & Kjaer).

The prototype of an ultrasonic array consisting of eight PMN - 32PT crystal strips with the λ/4 matching elements operating in the transverse extension mode was manufactured (Fig. 6a). The individual elements in the array were separated by spacing elements made of FinFoam with dimensions (2 x 3 x 5) mm^3. Spatial distributions of displacements inside piezoelectric elements and matching strips were obtained by FEM (Fig. 6b).

Experimental investigations were carried out by the laser Doppler vibrometer. The laser vibrometer was used to record mechanical displacements of the active surface of the transducer in continuous and transient modes.

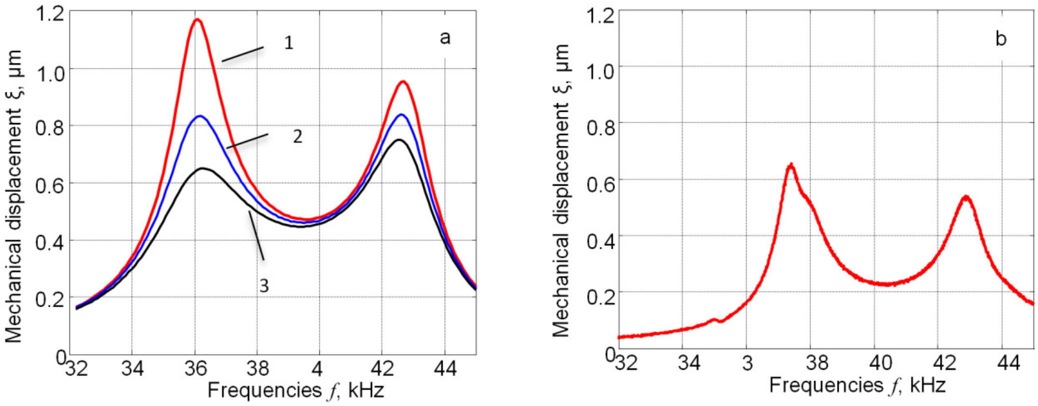

Fig. 4. Frequency responses of the PMN-PT element with the matching strip: (a) simulated by FEM, attenuation β in the matching strip: 1 – 2*10^{-7}; 2 – 3*10^{-7}; 3 – 4*10^{-7}; (b) measured by the laser interferometer.

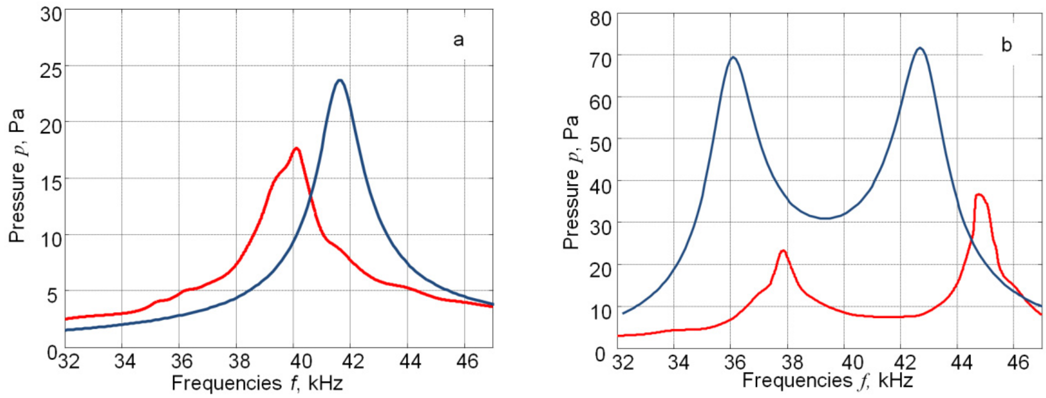

Fig. 5. Frequency responses in air: (a) the single element; (b) the matching strip; simulated by FEM (blue) and measured by the B&K 4138 type microphone with attenuation in the matching strip β=2*10^{-7} (red).

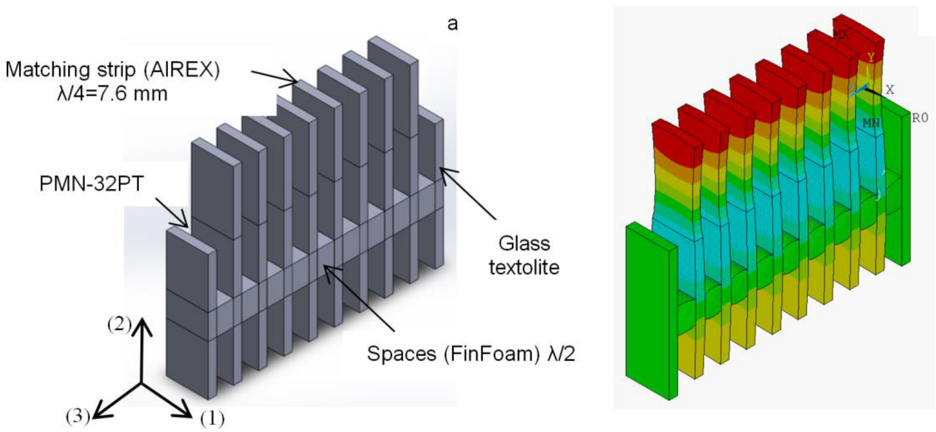

Fig. 6. Air – coupled ultrasonic array: (a) design;
(b) spatial distributions of displacements at the frequency f_r=49.3 kHz.

The colour scale in each figure depicts the amplitude of mechanical displacements. The red and blue colours correspond to the maximal values of displacements in opposite directions. Green colour corresponds to the minimal values of displacements. A good agreement between finite element simulation and measurement results was observed. The simulation has shown that vibrations and frequency responses of the individual elements in the array are very close to the corresponding responses of the single element shown in Fig. 4a and Fig. 5a.

The PMN-32PT single element transformation coefficient k_2 is 25 times better than of the PZT-29 element (f_r=50 kHz) and the mechanical displacement ξ is 11 times better than of the similar PZT-29 element with the matching strip.

3. Conclusions

Very high piezoelectric properties of the lead magnesium niobate - lead titanate (PMN-32%PT crystals) allow development of a new type of air-coupled ultrasonic transducers. The high electromechanical factor of the transverse extension mode helps to achieve a good performance. The developed and investigated ultrasonic transducer possesses in a transmission mode a few times better efficiency than a conventional air-coupled PZT composite ultrasonic transducer.

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