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ScienceDirect
Sensors and Actuators A 132 (2006) 434–440
SENSORS AND ACTUATORS A PHYSICAL
www.elsevier.com/locate/sna

PMN–PT single-crystal transducer for non-destructive evaluation

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Received 10 August 2005; received in revised form 1 February 2006; accepted 15 February 2006
Available online 29 March 2006

Abstract

A lead magnesium niobate–lead titanate (PMN–PT) single-crystal disc was used to construct an ultrasonic transducer for non-destructive evaluation (NDE). The surface displacements (at the thickness mode resonance) of the PMN–PT single crystal and a PZT disc of similar dimensions were measured using a laser scanning technique. It was observed that the PMN–PT disc has rather uniform ultrasonic displacements across its surface while the PZT exhibited an interference pattern indicative of coupling of the radial mode vibration with the thickness mode. This is consistent with the electrical impedance versus frequency measurements showing that for the PZT disc, a strong radial mode with many harmonics were clearly observed, and unwanted peaks existed near the thickness mode resonance. However, for the PMN–PT single-crystal disc, many resonance peaks were observed near the radial mode resonance but the harmonics of the radial mode cannot be identified. The PMN–PT disc has a clean thickness mode resonance peak and a high thickness electromechanical coupling coefficient. The discs were mounted in stainless steel housings with appropriate electrical connections to form transducers. Tungsten/epoxy backing and aluminum/epoxy front-face matching were incorporated to provide the necessary performance of very short ringdown times required for NDE applications. The characteristics of the PMN–PT transducer were compared with that of a PZT transducer of similar construction.

Keywords: PMN; PZT; Transducers; NDE; Non-destructive evaluation

1. Introduction

Lead magnesium niobate, with 33 mol% of lead titanate (0.67PMN–0.33PT, abbreviated as PMN–PT), single crystals with high piezoelectric coefficients ($d_{33} > 1700$ pC/N) and electromechanical coupling coefficients ($k_{33} > 0.9$) have attracted considerable attention [1–5], and their use in various devices has also been actively pursued [6–8]. For comparison, the commonly used piezoelectric ceramic lead zirconate titanate (PZT) has a d_{33} of ∼600 pC/N and a k_{33} of ∼0.75. The PMN–PT single crystals have been shown to provide better sensitivity and bandwidth than PZT when used in medical imaging transducers [8–10]. However, little has been reported on the use of these single crystals in transducers for non-destructive evaluation applications. To reduce the 'dead time' of the transducer for receiving return echoes, an NDE transducer is required to have a highly attenuative backing, matched to the impedance of the piezoelectric element, that will eliminate the backwall reflections in order to provide a short ringdown time. In this work, two immersible transducers have been fabricated, one employing a PMN–PT single crystal as the active element and the other using a commercial crystal of Pz29 [11]. The characteristics of each of these transducers at various stages of their construction have been measured and compared. This will help determine whether transducers made in the same way but with two different active elements (PZT and PMN–PT) display similar characteristics, and in particular if PMN–PT transducers may be used effectively in NDE applications.

2. Experimental procedure

The PMN–PT single crystal used in this work was grown by a modified Bridgman method at the Shanghai Institute of Ceramics [12–14]. The 1-mm thick, 10-mm diameter PMN–PT disc with thickness along the ⟨1 0 0⟩ direction was prepared and chromium/gold electrodes were applied to both sides of the disc

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doi:10.1016/j.sna.2006.02.024

Table 1
Properties of PMN–PT single-crystal and PZT (Pz 29) ceramics

	PMN–PT	PZT
Density, ρ (kg/m^3)	7852	7450
Relative permittivity at 1 kHz, ε_{33}^{T}	5569	2900
Dissipation factor tan δ at 1 kHz ($\times 10^{-3}$)	3.6	19
Thickness electromechanical coupling coefficient, k_t	0.61	0.52
Piezoelectric charge coefficient, d_{33} (10^{-12} C/N)	1720	575
Piezoelectric voltage coefficient, g_{33} (10^{-3} Vm/N)	34.9	23
Frequency constant (thickness mode), N_t^D (Hz m)	1935	1960
Mechanical quality factor, Q_M	72	90

by magnetron sputtering. It was poled by applying 1 kV/mm at 130 °C for 10 min in a silicone oil bath. The electric field was maintained while the sample was cooled to ~60 °C. The measured parameters of the PMN–PT discs used in these experiments are shown in Table 1. A poled PZT (Pz29) disc with similar dimensions was purchased from Ferroperm, Denmark [11], and its properties, provided by Ferroperm, are also shown in Table 1. Properties of the bare, poled discs were measured in two ways. Firstly, the electrical impedance and phase versus frequency spectra of both the PMN–PT and PZT discs were measured using an impedance analyzer (HP4294A). Secondly, each of the PMN–PT and PZT discs were mounted onto an x–y motion stage and driven at their thickness mode resonance frequency using a tone-burst sine wave generated by a function generator (HP8116A) and a power amplifier giving an output amplitude of 10 V. This allowed a laser vibrometer (Polytec OVF2700) to be used to measure the ultrasonic out-of-plane displacements generated on the front face of each disc (in air) by raster scanning the laser beam across their surfaces.

Two transducers with similar structure were fabricated using the PMN–PT and PZT discs as their driving elements. The transducers have tungsten powder/epoxy backing (~8 mm thick with a tungsten:epoxy ratio of 16:1 by weight. A low-viscosity epoxy, Epotek 301, was used. A front face matching layer consisting of Al:epoxy in the weight ratio 2.5:1 was applied. Fig. 1 shows a photograph of the completed transducers.

Fig. 1. Photograph of the PMN–PT and PZT transducers.

The pulse-echo response and insertion loss of the PMN–PT and PZT discs as well as the PMN–PT and PZT transducers were measured and compared. The transducer (or the disc) was mounted in a water tank in front of a stainless steel target block which had a plane circular cross-section presented to the transducer, and was connected to a Panametrics model 5052UA ultrasonic transducer analyzer. The distance between the transducer and the block was chosen to be the near field/far field transition distance T, given approximately by:

$$T = \frac{a^2}{\lambda}, \qquad (1)$$

where a is the radius of the transducer element (= 5 mm) and λ is the wavelength in water at the centre frequency of the transducer.

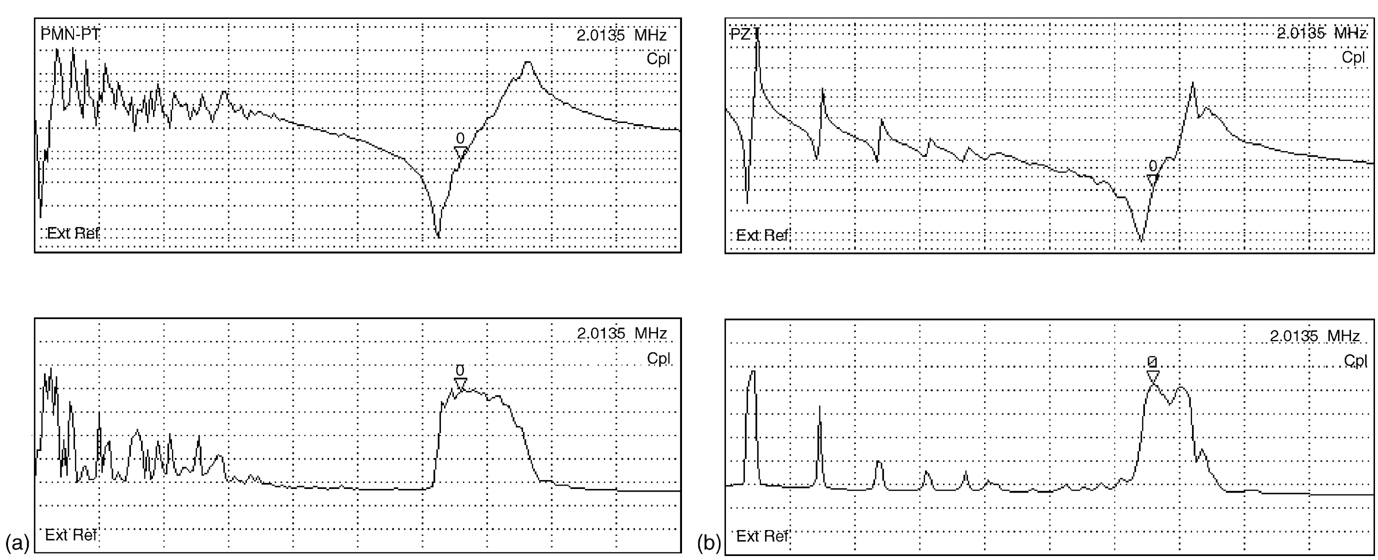

Fig. 2. (a) Impedance (upper) and phase (lower) as functions of frequency for the PMN–PT disc. Horizontal scale is frequency, linear from 0.1 to 3.0 MHz. Vertical scales: impedance, logarithmic from 5 Ω to 5 kΩ; phase, linear from 0° to 100°. (b) Impedance (upper) and phase (lower) as functions of frequency for the PZT disc. Horizontal scale is frequency, linear from 0.1 to 3.0 MHz. Vertical scales: impedance, logarithmic from 5 Ω to 10 kΩ; phase, linear from 10° to 110°.