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Comprehensive analysis of Mn:PIN-PMN-PT single crystals for Class IV flextensional transducer

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ABSTRACT

As a crucial part of flextensional transducer (FT), the piezoelectric stack has an essential influence on the transducer. However, up to date, there are no literatures on considering the loss characteristics of the piezoelectric materials in the design of FT. Manganese-modified PIN-PMN-PT (Mn:PIN-PMN-PT) single crystals have greatly improved Q_m values compared with the binary and ternary single crystals. In this paper, Class IV FTs based on Mn:PIN-42%PMN-32%PT and Mn:PIN-47%PMN-29%PT crystals were analyzed comprehensively on the heat losses, as well as transmitting voltage response (TVR), source level (SL), acoustic pressure (AP) and admittance. Compared with PIN-47%PMN-29%PT, PMN-28%PT and PZT4, the Mn:PIN-42%PMN-32%PT FT has a decrease of heat loss by 47.9%, 79.5% and 93.6%, respectively, under the same strain of 5×10^{-5}. The results indicated that the Mn:PIN-PMN-PT FT possesses simultaneously the less heat loss and lower resonant frequency, the higher AP, TVR, SL and effective electromechanical coupling coefficient. This research provides a guide for the design of FT and illuminates the immense potential of Mn:PIN-PMN-PT single crystals in making low heat generation, low frequency and high power FT.

1. Introduction

The Class IV flextensional transducer (FT), which is a typical low frequency, high power and small size transducer, is widely applied in underwater acoustic projector [1]. Many researchers have focused on the design of the transducer structure. However, in the practical application, transducers usually work under the high driving voltage and vibration amplitude. Internal losses occur inevitably and are converted into heat [2]. High power and long term usage of the transducer will cause accumulation of the heat inside the transducer, which can result in temperature rise of the transducers [3]. Excessive temperature rise will seriously deteriorate the performance and the reliability life of the transducer. In recent years, heat problem has drawn considerable attentions. Roh and Kang simulated the effects of the shell sizes on the temperature of the FT by finite element method [3]. However, the effect of piezoelectric material dissipation for the transducer wasn't considered. As a crucial part that transform electrical energy to mechanical energy, the properties and thermal loss of piezoelectric material have an essential influence on the transducer in high power applications. For the underwater transducers, the features of lower driving frequency, wider frequency band and less power loss are desired. Therefore, it is necessary to consider the loss characteristics of the piezoelectric materials, as well as the acoustic parameters in the design of the FT.

Over the past decades, relaxor-based single crystals have attracted much attention owing to their ultrahigh piezoelectric coefficients ($d_{33} > 1500$ pC/N) and electromechanical coupling factors ($k_{33} > 0.90$). The first generation single crystals, such as $Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$ (PMN-PT), have been used in Tonpilz transducer [4]. Compared with conventional $Pb(Zr,Ti)O_3$ (PZT) piezoelectric ceramics, PMN-PT has been demonstrated to possess improvements of the bandwidth and source level of the transducers [5–11]. However, the binary crystals possess low coercive field E_c (~ 2–3 kV/cm), low mechanical quality factor Q_m (~ 190), low rhombohedral-to-tetragonal phase transition temperature (T_{RT} ~ 60–100 °C), restricting their practical applications in the high power transducer. The second generation single crystals, ternary $Pb(In_{1/2}Nb_{1/2})O_3$-$Pb(Mb_{1/3}Nb_{2/3})O_3$-$PbTiO_3$ (PIN-PMN-PT), have higher T_C (being on the order of 180–220 °C), and higher coercive field E_c (being on the order of ~ 5 kV/cm) than PMN-PT, showing much improvement of temperature stability and electric field stability, while maintaining the competence in piezoelectric coefficients ($d_{33} > 1500$ pC/N) and electromechanical coupling factors ($k_{33} > 0.90$) [11]. For high power applications, high Q_m value is desired to reduce heat generation. However, PIN-PMN-PT has not improved much in the Q_m value (~ 290).

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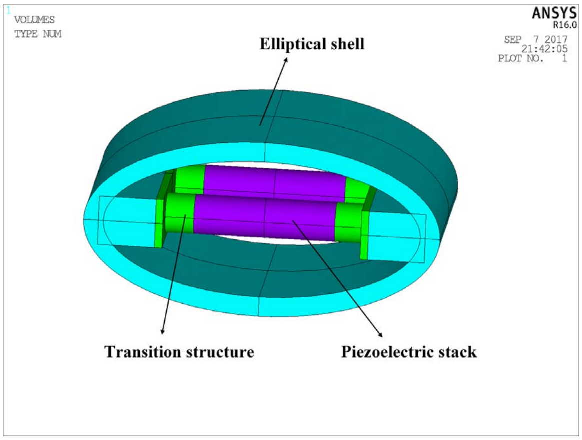

Fig. 1. The whole finite element transducer model in air.

Recently, the third generation crystals, manganese-modified PIN-PMN-PT (Mn:PIN-PMN-PT) crystals have greatly improved Q_m value (~ 810), which is comparable to that of the hard PZT ceramics. Compared with the ternary single crystals, Mn:PIN-PMN-PT has similar piezoelectric properties. Considering of much enhanced Q_m value and a moderate increment in the phase transition temperature by the addition of Mn, together with the comparable piezoelectric and electromechanical properties, Mn:PIN-PMN-PT single crystal will be a potential candidate for high power FT. However, up to date, there are no reports in the literature on the effects of Mn:PIN-PMN-PT single crystal on FT by considering simultaneous energy losses and underwater acoustic properties.

In this work, comprehensive analysis of a class IV FT based on Mn:PIN-PMN-PT crystals is performed. The effects of PT component for Mn:PIN-PMN-PT crystals (Mn:PIN-42%PMN-32%PT and Mn:PIN-47% PMN-29%PT) on the FTs are discussed. Meanwhile, the properties of the class IV FTs based on Mn:PIN-PMN-PT crystals are investigated and compared with binary PMN-PT crystal, ternary PIN-PMN-PT crystal, and conventional PZT ceramic by considering simultaneously energy losses, admittance, bandwidth, transmitting voltage response (TVR), source level (SL) and acoustic pressure (AP). The intent of this work is to perform a global analysis and illuminate the potential of Mn:PIN-PMN-PT single crystal in making less energy loss, low frequency and high power FTs.

2. Model and material constants of the transducer

In our works, Class IV FT consists of a pair of cylindrical piezoelectric stack that serve as the active driver and an elliptical shell that serves as an acoustic radiator, just as shown in Fig. 1. Because of the displacement amplification effect provided by elliptic shell based on leverage effect, small extensional displacement produced by piezoelectric stacks is transmitted into large volume displacement on the elliptical shell, which can output the acoustic radiated power.

To address the effect and the advantage of Mn:PIN-PMN-PT crystal on the FT, the material properties of Mn:PIN-42%PMN-32%PT, Mn:PIN-47%PMN-29%PT single crystals, as well as PIN-47%PMN-29% PT, PMN-28%PT and PZT4, are listed and compared in Table 1. Material parameters ρ, T_{RT}, d_{33}, ε_{33}^T, k_{33}, E_c, Q_m, $tan\delta$, s_{33}^T represent density, rhombohedral-to-tetragonal phase transition temperatures, piezoelectric coefficient relating strain/electric field, dielectric permittivity, coercive field, mechanical quality factor, dielectric loss factor and elastic compliance constant, respectively.

Table 2
The sizes of the class IV FT.

Parameter (mm)		Parameter (mm)	
Semi Minor axis length	36	Semi major axis length	72
Shell thickness	8	Shell height	90
Piezoelectric stack length	28.5	Piezoelectric stack radius	8

In order to calculate conveniently, one eighth of the whole finite element model is set up using commercial finite element software ANSYS. The sizes are shown in Table 2. The models in air and water environment are shown in Fig. 2. In this model, the aluminum material and stainless steel are applied on the cylindrical shell and transition structure, respectively. The piezoelectric materials listed in Table 1 are selected as the drive materials. In addition, fluid-structure coupling load was imposed on the fluid-structure interface (FSI) layer, which represents the interaction between the water and the transducer. Then all the analyses are performed in water environment.

3. Results and discussions

For the underwater transducers, general characterization that includes corresponding admittance spectrum, TVR, SL, AP are investigated to evaluate the performance of transducer.

3.1. The analysis of the admittance

The in-water admittance spectra of FTs based on the five materials are simulated and shown in Fig. 3. The peaks with maximum and minimum admittance corresponds to the resonant frequency f_r and anti-resonant frequency f_a of the FTs, respectively. Generally, the resonant frequency is mainly determined by shell shape of the transducer [19]. However, because the shells are the same in all simulations for the five drive materials in this paper, the differences of admittance curves of FTs are mainly caused by its drive materials.

The differences of the resonant frequencies of FT based on the five piezoelectric materials can also be observed from Fig. 3. The FTs driven by all four single crystals present lower frequencies than PZT4 PT. Among these crystals, the Mn:PIN-PMN-PT transducers exhibit better low-frequency performances than counterparts. Especially, the Mn:PIN-42%PMN-32%PT FT, which possesses the lowest resonance frequency, is 150 Hz and 450 Hz lower than PMN-28%PT and PZT4 FTs, respectively. This demonstrated that the manganese-modified crystal is the most appropriate choice for fabricating low frequency FTs.

In addition, the effective electromechanical coupling coefficient (k_{eff}), which is a key parameter to evaluate the performance of transducer and represents the energy conversion capacity, can be calculated

Table 1
The characteristics comparison of Mn:PIN-PMN-PT, PMN-PT, PIN-PMN-PT single crystals and PZT4 [9,12–18].

Material	ρ kg/m^2	T_{RT} °C	d_{33} pC/N	ε_{33}^T ε_0	k_{33} /	E_c kV/cm	Q_m, %	s_{33}^T 10^{-12} m^2/N	$tan\delta$ %
Mn:PIN-42%PMN-32%PT	8100	128	1341	3811	0.92	11.5	810	64.96	0.16
Mn:PIN-47%PMN-29%PT	8173	128	855	2599	0.86	11.5	810	43.07	0.16
PIN-47%PMN-29%PT	8122	125	1285	4753	0.89	5.0	290	49.04	0.15
PMN-28%PT	8095	95	1182	5479	0.91	2.5	190	34.30	0.26
PZT4	7500	/	289	1300	0.74	14	500	15.0	0.3