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Cymbal actuator fabricated using $(Na_{0.46}K_{0.46}Li_{0.08})NbO_3$ lead-free piezoceramic

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Abstract $(Na_{0.46}K_{0.46}Li_{0.08})NbO_3$ (NKLN8) lead-free piezoceramic was prepared by a mixed oxide route. The ceramic showed a single phase of orthorhombic perovskite structure at room temperature and a high Curie temperature of ~430°C. A cymbal actuator using NKLN8 as the actuation element and titanium alloy as the endcaps was fabricated and characterized. A similar actuator with traditional $Pb(Zr,Ti)O_3$ (PZT) piezoceramic was also constructed for comparison. The results showed that the NKLN8 actuator has a higher fundamental resonance frequency of 107.1 kHz and a faster response of 9.3 μs with a comparable effective coupling coefficient of 0.15 at the expense of a lower strain coefficient of 1.9 nm/V. The observed actuator performance was discussed in relation to the ceramic properties.

Keywords Cymbal actuator · Lead-free piezoceramic · NKLN8 · PZT

Introduction

Cymbal actuators, which possess an intermediate displacement and force capability in comparison with only large forces in multilayer actuators and only large displacements in bimorph actuators, are classified as class V flextensional actuators [1, 2]. As shown in Fig. 1, a cymbal actuator is essentially a metal-ceramic composite device consisting of a thickness-polarized piezoceramic disc sandwiched between two truncated conical metal endcaps [1]. In operation, an electric field applied along the thickness direction of the piezoceramic disc results in a radial motion of the disc. This radial motion is subsequently converted into flexural and rotational motions in the endcaps, leading to a considerable axial displacement and force output based on the stiffness of the endcaps.

Similar to other piezoelectric actuators, cymbal actuators are typically made of $Pb(Zr, Ti)O_3$ (PZT) ceramics owing to their high Curie temperatures and superior electromechanical properties [1, 2]. In fact, the treatment of PbO in PZT compositions causes significant pollution on the environment [3]. Lead-free piezoceramics have attracted much attention as eco-ferroelectric materials in recent years [4, 5]. Among them, perovskite-type niobate-based ceramics, such as $(Na,K)NbO_3$ (NKN)-based compositions, have been recognized as a good candidate as they possess relatively high Curie temperatures, large electromechanical properties, and low densities [6]. Nevertheless, their application potential for actuators has not yet been demonstrated.

In this work, we aim to study the crystal structure and electromechanical properties of $(Na_{0.46}K_{0.46}Li_{0.08})NbO_3$ (NKLN8) ceramic as well as to explore the potentiality of using NKLN8 to fabricate cymbal actuators. For comparison purposes, cymbal actuators using a traditional $Pb(Zr, Ti)O_3$ (PZT) ceramic (i.e., PKI802) is also fabricated and characterized.

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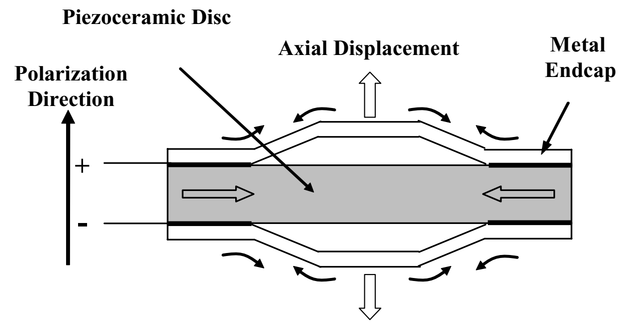

Fig. 1 Schematic diagram of a cymbal actuator

Experimental

NKLN8 and PKI802 ceramics

NKLN8 ceramic was prepared by the conventional mixed oxide route [5]. Commercial metal-carbonate powders Na_2CO_3, K_2CO_3, and Li_2CO_3, and metal-oxide powder Nb_2O_5, all with purities higher than 99%, were used as starting materials. Calcination of the mixture was conducted at 880°C for 2 h. The mixture was pelletized using a PVA binder and pressed uniaxially into disks. The disk samples were sintered at 1080°C for 2 h and then ground into 10 mm diameter and 0.9 mm thickness. The crystal structure of the sintered samples was examined using an X-ray diffractometer (Xpert System, Philips). Silver paste was applied on the two flat surfaces of the disk samples and fired at 650°C as electrodes for the subsequent poling under a dc electric field of 6.5 kV/mm at 160°C in a silicone oil bath for 20 min. Besides NKLN8 disks, PZT disks of the same dimensions were also prepared using PKI802 powder (Piezo Kinetics, Inc., USA). Detailed procedure for preparing PKI802 disks can be found from our earlier work [5].

The density (ρ) of both NKLN8 and PKI802 samples was determined using Archimedes' method. The temperature dependence of relative permittivity (ε_r) and dissipation factor (tanδ) at different frequencies was measured using an impedance analyzer (HP 4194A) and a programmable furnace (ESPEC SU-240). The planar coupling coefficient (k_p) and planar frequency constant (N_p) were determined using an impedance analyzer (Agilent 4294A) according to the resonance method [7]. The thickness charge coefficient (d_{33}) was measured at 110 Hz using a piezo d_{33} meter. The transverse charge coefficient (d_{31}) was deduced using $d_{31} = (d_h - d_{33})/2$, where the hydrostatic coefficient (d_h) was measured with a PMMA hydrostatic chamber filled with silicone oil [8].

NKLN8 and PKI802 cymbal actuators

The truncated conical metal endcaps as shown in Fig. 1 were made by die-punching a titanium alloy sheet of ~0.3 mm thick. NKLN8 and PKI802 disks were, respectively, bonded between two endcaps using an epoxy adhesive (Araldite LY5138/HY5138).

The performance of both NKLN8 and PKI802 actuators was evaluated by measuring their electrical and mechanical characteristics. The electrical measurements involved capturing their complex electrical impedance spectra using an impedance analyzer (Agilent 4294A) and then determining their effective coupling coefficients ($k_{eff} = \sqrt{1-(f_r/f_a)^2}$) and fastest response times ($t_{FRT} = f_r^{-1}$) based on the observed fundamental resonance (f_r) and anti-resonance (f_a) frequencies [1]. The mechanical measurements included driving the actuators under an ac electric field of 0.1 kV/mm at 10 kHz and then measuring their axial displacement distributions along the diameter of the endcaps using an outplane laser Doppler vibrometer (Polytec OFV-3300-2).

Results and discussion

NKLN8 and PKI802 ceramics

Figure 2 shows the X-ray diffraction pattern of NKLN8 ceramic. It is recalled that, at room temperature, $NaNbO_3$ is antiferroelectric with an orthorhombic structure; $KNbO_3$ is ferroelectric with an orthorhombic structure; and $LiNbO_3$ is ferroelectric with a trigonal structure [9]. Only a single-phase orthorhombic perovskite structure observed here for NKLN8 suggests that all constituent components form a solid solution.

The temperature dependence of ε_r and tanδ of NKLN8 ceramic at different frequencies is illustrated in Fig. 3. It is seen that NKLN8 has Curie temperature (T_c) as high as ~430°C. A small change at ~180°C reflects the orthorhombic-to-tetragonal structural phase transition.

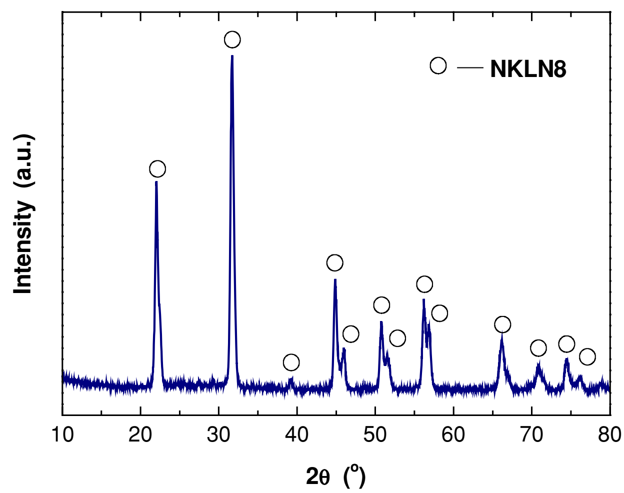

Fig. 2 X-ray diffraction pattern of NKLN8 ceramic

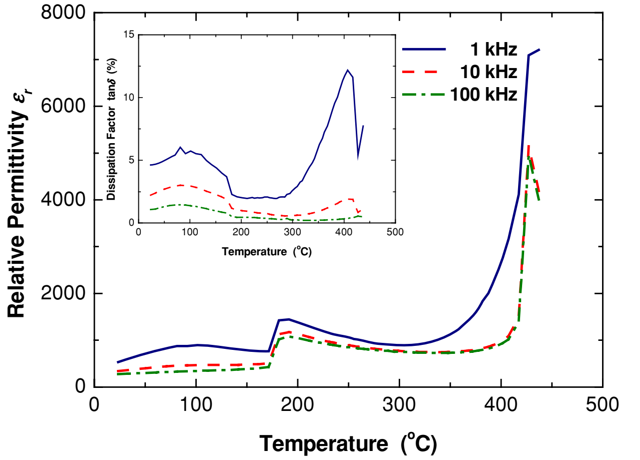

Fig. 3 Temperature dependence of relative permittivity (ε_r) and dissipation factor (tanδ) of NKLN8 ceramic at different frequencies

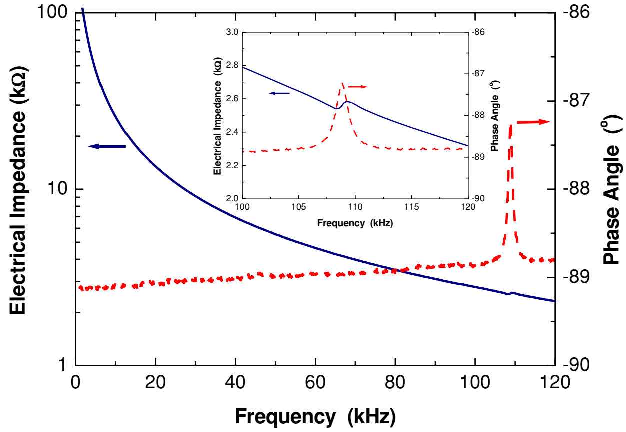

Fig. 4 Complex electrical impedance spectrum for NKLN8 cymbal actuator

The measured properties of both NKLN8 and PKI802 ceramics are summarized in Table 1.It is clear that NKLN8 has a higher T_c, a lower ρ, and a smaller N_p. However, it suffers from a higher tanδ and lower ε_r, k_p, d_{33}, and d_{31}.

NKLN8 and PKI802 cymbal actuators

Figure 4 plots the complex electrical impedance spectrum for the NKLN8 actuator up to and beyond its fundamental resonance frequency (f_r), while Table 2 shows the measured f_r, t_{FRT}, and k_{eff} of both NKLN8 and PKI802 actuators. As shown in Table 2, f_r of NKLN8 actuator (i.e., 107.1 kHz) is 22 kHz higher than that of PKI802 actuator (i.e., 85.1 kHz). The reason may be explained by the existence of a higher N_p and a lower ρ in the NKLN8 ceramic (Table 1). Nevertheless, this increased f_r in NKLN8 actuator has resulted in much faster response (i.e., $t_{FRT} = 9.3\mu$s) as compared with PKI802 actuator (i.e., 11.8 μs). Both actuators exhibit comparable k_{eff} (i.e., 0.15 for NKLN8 and 0.16 for PKI802) even though k_p is relatively smaller for the NKLN8 ceramic (Table 1). This may be attributed to a better acoustic impedance matching between the NKLN8 ceramic and the titanium alloy [10].

Table 1 Properties of NKLN8 and PKI802 ceramics

Ceramic properties	NKLN8	PKI802
T_c (°C)	430	350
ρ (kg/m^3)	4060	7570
ε_r at 1 kHz	532	841
tanδ at 1 kHz (%)	4.6	0.7
k_p	0.40	0.48
N_p (Hz·m)	3500	2445
d_{33} (pm/V)	106	215
d_{31} (pm/V)	−47	−82

Table 2 Properties of NKLN8 and PKI802 cymbal actuators

Actuator properties	NKLN8	PKI802
f_r (kHz)	107.1	85.1
t_{FRT} (μs)	9.3	11.8
k_{eff}	0.15	0.16

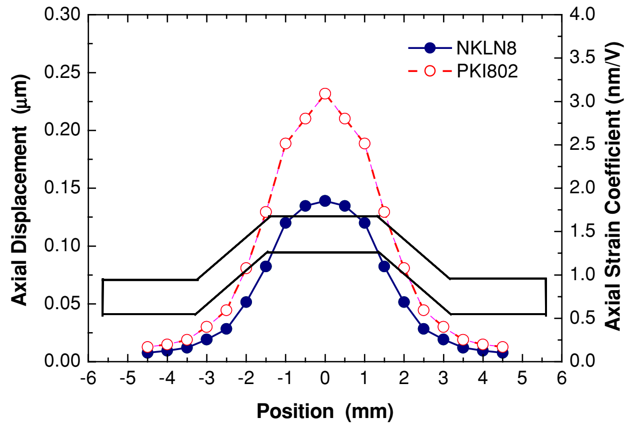

Fig. 5 Axial displacement distributions of NKLN8 and PKI802 cymbal actuators

The axial displacement distributions of NKLN8 and PKI802 actuators are shown in Fig. 5. Both actuators show similar distributions to the shape of the endcaps with the maximum amplitude located around the centre of the endcaps. The displacement amplitudes are generally smaller for the NKLN8 actuator due to the lower d_{33} and d_{31} in the NKLN8 ceramic [1]. The maximum displacement amplitudes for NKLN8 and PKI802 actuators are found to be 0.14 μm and 0.23 μm, respectively, which in turn result in the maximum strain coefficients of 1.9 nm/V and 3.1 nm/V.

Conclusion

Lead-free NKLN8 piezoceramic has been prepared and characterized for cymbal actuator application. Lead-based PKI802 piezoceramic and cymbal actuator have also been produced for comparison. While NKLN8 ceramic has a higher T_c, it experiences a smaller ε_r and a larger tanδ. Since NKLN8 ceramic has a lower ρ and a higher N_p, the resulting cymbal actuator shows a higher f_r, together with a smaller t_{FRT}. k_{eff} is comparable for both actuators in spite of a lower k_p for the NKLN8 ceramic. As NKLN8 ceramic has relatively small d_{33} and d_{31}, the resulting field-induced displacement is lower.

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