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Ring-Type Rotary Ultrasonic Motor Using Lead-free Ceramics

Chang-Hyo Hong[1], Hyoung-Su Han[1], Jae-Shin Lee[2], Ke Wang[3], Fang-Zhou Yao[3], Jing-Feng Li[3], Jung-Ho Gwon[4], Nguyen Van Quyet[4], Jin-Kyung Jung[2], and Wook Jo[1,+]

Abstract

Ultrasonic motors provide high torques and quick responses compared to their magnetic counterparts; therefore, they are widely used in small-scale applications such as mobile phones, microrobots, and auto-focusing modules in digital cameras. To determine the feasibility of lead-free piezoceramics for ultrasonic motor applications, we fabricated a ring-type piezoceramic with a KNN-based lead-free piezoceramic (referred to as CZ5), intended for use in an auto-focusing module of a digital camera. The vibration of the lead-free stator was observed at 45.1 kHz. It is noteworthy that the fully assembled lead-free ultrasonic motor exhibited a revolution speed of 5–7 rpm, even though impedance matching with neighboring components was not considered. This result suggests that the tested KNN-based piezoceramic has great potential for use in ultrasonic motor applications, requiring minimal modifications to existing lead-based systems.

Keywords: Ultrasonic motors, Lead-free, $(K_{0.5}Na_{0.5})NbO_3$, Piezoelectrics, Auto-focusing module

1. INTRODUCTION

Because the RoHS (Restriction of Hazardous Substances) directive has been effective in the European Union; the development of environmentally friendly materials with salient properties for electronic applications has been of great interest to the electronic materials community. Successive release of tougher regulations similar to RoHS worldwide has made the lead-free community one of the biggest within the electronic materials community. In spite of great effort over more than two decades, the market has seen only a few cases in which lead-free piezoceramics have been utilized in consumer products. This is because the piezoelectric properties of market-dominating PZT-based piezoceramics are very good and easy tunable; no known lead-free piezoceramics can compete with their versatility. This means that technology transfer to industry has seldom been attempted; a material that competes with PZT-based materials in terms of both properties and versatility is eagerly anticipated [1-5]. Although not yet satisfactory, $Bi_{1/2}Na_{1/2}TiO_3$ (BNT), $K_xNa_{(1-x)}NbO_3$ (KNN), and their derivatives in the form of solid solutions are generally considered the most promising materials [4,6-8].

Recently, we reported a highly promising lead-free piezoceramic with a nominal composition of $0.95(Na_{0.49}K_{0.49}Li_{0.02})(Nb_{0.8}Ta_{0.2})O_3$-$0.05CaZrO_3$ with 2 wt% MnO_2 addition, (referred to as CZ5), which shows highly temperature-insensitive and fatigue-resistant electric-field-induced strains [9]. The piezoelectric coefficients d_{33} and d_{33}^* (S_{max}/E_{max}) reach 320 pC/N and 0.13% (at 4 kV/mm), respectively, at room temperature. It is noteworthy that although d_{33} varies significantly with increasing temperature, d_{33}^* remains almost the same up to temperatures as high as 175 °C (variations

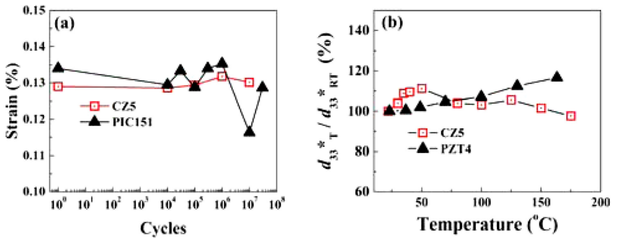

Fig. 1. Strain of CZ5 (a) as a function of cycles, (b) as a function of temperature.

[1]School of Materials Science and Engineering, Ulsan National Institute of Science and Technology, 50 UNIST-gil, Ulsan 689-798, Republic of Korea
[2]School of Materials Science and Engineering, University of Ulsan, 93 DaeHak-Ro, Ulsan 680-749, Repulic of Korea
[3]State Key Laboratory of New Ceramics and Fine Processing, School of Materials Science and Engineering, Tsinghua University, Beijing 100084, China
[4]HanaUtech, Techno 10-Ro, DaeJeon 305-510, Repulic of Korea
[+]Corresponding author: wookjo@unist.ac.kr
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of less than ±10%) [9]. This temperature-insensitive strain degrades by only as much as ±3%, even up to 10^7 cycles at 50 Hz at room temperature (as shown in Fig. 1) [10].

To quickly assess the suitability of CZ5 for commercial applications, we fabricated a ring-type piezoceramic ultrasonic motor (USM) to be embedded in a commercialized auto-focusing module in a digital camera. Although no mechanical impedance matching was applied between CZ5 and neighboring components such as the stator and rotor, the USM propelled by CZ5 exhibits good performance, which makes CZ5 a highly promising candidate for USM applications.

2. EXPERIMENTAL

The oxides and carbonates; (Alfa Aesar GmbH & Co. KG, Karlsruhe, Germany), Li_2CO_3 (99.0%), Na_2CO_3 (99.5%), K_2CO_3 (99.0%), Nb_2O_5 (99.5%), Ta_2O_5 (99.0%), $CaCO_3$ (99.5%), ZrO_2 (99.5%), and MnO_2 (99.5%); were mixed according to the previously reported chemical formula of $0.95(Na_{0.49}K_{0.49}Li_{0.02})(Nb_{0.8}Ta_{0.2})O_3$-$0.05CaZrO_3$ with 2 wt% MnO_2, followed by ball-milling for 24 h in ethanol [9]. The ball-milled powder was calcined at 900°C for 4 h and ball-milled again for 24 h. Polyvinyl alcohol (PVA), as a binder, was added into the calcined powder before being pressed into ring-type disks of 77.4 mm in external diameter, 68.4 mm in internal diameter, and 1.0 mm in thickness under a pressure of 100 MPa. These ring-type samples were sintered in air at 1150°C for 2 h.

Sintered samples were ground and polished to a thickness of 0.4 mm, and then painted with a silver paste using a specially designed electrode pattern. After burning out the silver paste at 700°C, the external side of the pellets was trimmed to fit the poling jig because of uneven shrinkage. Specimens were poled at 2.5 kV/mm and 30°C in a silicon oil bath for 30 min in such a way that positively and negatively poled regions were alternately induced. To fabricate the assembled motor, poled samples were glued onto a stator attached to a flexible printed circuit board (FPCB) under a pressure of 534 kPa at room temperature for 24 h.

The piezoelectric coefficient of the ceramic samples was measured using a d_{33} testing meter (ZJ-3A, Institute of Acoustics, Chinese Academy of Sciences). The resistance and capacitance of the stator were measured using a multimeter (Fluke 177 digital multimeter, Fluke Corporation, USA). The revolution speed and torque were measured using a customized tester.

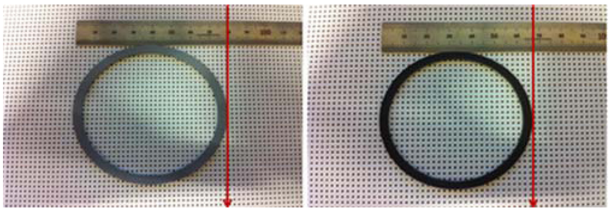

Fig. 2. Ring-type CZ5 specimen (a) before and (b) after sintering.

Table 1. Material constants of CZ5

Type	Dielectric permittivity (ε_r)	tanδ (%)	d_{33} (pC/N)	k_p (%)	Q_m
Disk	1735	2.10	320	47	50
Ring-type	1262	3.42	85	18	103

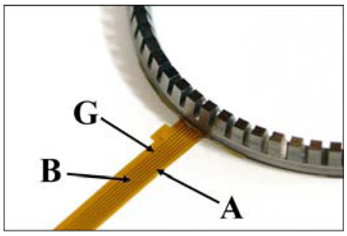

Fig. 3. A, B, and ground (G) points of stator.

3. RESULTS AND DISCUSSIONS

Fig. 2 shows that the ring-type pellets for use in ultrasonic motors were prepared with maximum tolerances in thickness and diameter of ±10 μm and ±100 μm, respectively, to guarantee stable revolution speed, minimal noise, and maximal durability. The specimens were ground and lapped to a final thickness of 0.4 mm (±9 μm).

Changes in the material parameters were observed between the disk pellets and ring-type samples, as shown in Table 1. The ring-type samples had a piezoelectric constant (d_{33}) of 85 pC/N, an electromechanical coupling factor (k_p) of 0.18, and a mechanical quality factor (Q_m) of 103. In other words, the d_{33} and k_p values were degraded by 74.3% and 61.7%, respectively; however, Q_m was enhanced by 106%.

To check how well the ceramic body was glued onto the stator and electrically connected, as shown in Fig. 3, resistance and capacitance were measured. The capacitance of PZT and CZ5 were 5.6–5.8 nF and 9.0–9.2 nF respectively.

The resistance of the CZ5 stator was similar to that of the commercial PZT. Additionally, the d_{33} value of CZ5 was almost the same before being glued onto the stator, as shown in Table 2.

The assembled USM motor module is shown in Fig. 4. The

Table 2. Resistance and capacitance of ultrasonic motors

Materials	d_{33} (pC/N)	Resistance (Ω)			Capacitance (nF)	
		A	B	G	A/G	B/G
CZ5	85	0.2	0.2	0.7	8.644	9.164
PZT	320	0.3	0.4	0.3	5.283	5.364

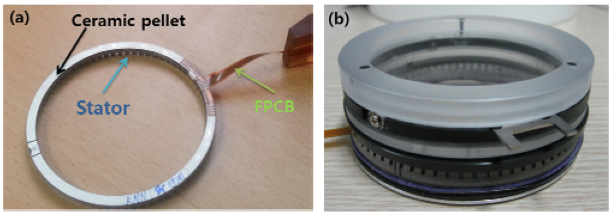

Fig. 4. Ring-type vibrator and motor: (a) stator vibrator, (b) ultrasonic motor.

Table 3. Mechanical properties of assembled stators

	Revolution speed (rpm)	Torque (gf-cm)	d_{33} (pC/N)	Operating frequency (kHz)
CZ5	5–7	~50	103	45.1
PZT	45–55	450	200–320	31–32

resonance of the CZ5 stator was found to be 45.1 kHz with an input voltage of 110-120 V_{p-p}. The ultrasonic motor using CZ5 had a revolution speed of up to 7 rpm with a torque of 50 gf·cm at 45.1 kHz. The PZT motor had a revolution speed of up to 55 rpm with a torque of 450 gf·cm at 31 kHz.

In spite of the overall inferior performance of CZ5 in comparison to PZT, CZ5 was found to have a lower power loss and enhanced electric power efficiency in operation because of its higher capacitance (relative to PZT). Power storage in a capacitor is $W = 1/2 \times C \times V^2$, which yields 5.39×10^{-5} J and 3.22×10^{-5} J for CZ5 and PZT, respectively.

In addition, the power loss in a capacitor corresponds to $2p \times f \times C \times V^2$ (tangent delta), which indicates that CZ5 (30 J·s) resulted in a higher power loss than PZT (12 J·s) because of the larger tangent delta and C values. This phenomenon could be one of the reasons for the lower speed and torque (in addition to the aforementioned impedance mismatch). Another reason for the lower torque in CZ5 might arise from the lower stiffness of CZ5, relative to that of PZT. The lower torque may be related to the force generated during operation. Because the force generation is given by $F = K$ (stiffness) $\times D$ (displacement) and the stiffness has no distinct difference between CZ5 and PZT [11], the lower torque value is considered to be caused by the lower displacement during operation.

4. CONCLUSIONS

This study reports a preliminary test of the feasibility of using a lead-free piezoceramic for commercial uses. Based on the current method of using PZT ultrasonic motors in commercial lenses, we successfully demonstrated a KNN-based lead-free piezoelectric ultrasonic motor. Although no optimization effort was made to maximize the performance of the device, the CZ5 embedded auto-focusing module exhibited reasonable functional performance. Two issues of importance to be further studied were identified: 1) the reason why the ring-type CZ5 samples showed lower piezoelectric properties but higher mechanical quality factor than the disk samples, and 2) the influence of mechanical impedance matching on the final performance of the USM.

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