J Mater Sci (2008) 43:709–714
DOI 10.1007/s10853-007-2199-0

A Rosen-type piezoelectric transformer employing lead-free $K_{0.5}Na_{0.5}NbO_3$ ceramics

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Received: 29 August 2007 / Accepted: 28 September 2007 / Published online: 31 October 2007

Abstract Lead-free $K_{0.5}Na_{0.5}NbO_3$–$K_{5.4}Cu_{1.3}Ta_{10}O_{29}$–$MnO_2$ (KNN–KCT–Mn) ceramics have been prepared by a conventional ceramic sintering technique. The ceramics show excellent piezoelectric properties for application in power devices, and the optimum properties measured are as follows: piezoelectric constant $d_{33} = 90$ pC/N, planar electromechanical coupling factor $k_p = 0.40$, mechanical quality factor $Q_m = 1900$, remanent polarization $P_r = 11.8\ \mu C/cm^2$, coercive field $E_c = 0.85$ kV/mm. A Rosen-type piezoelectric transformer with a dimension of 21 mm × 6 mm × 1.2 mm was fabricated using the KNN–KCT–Mn ceramics. Properties of the piezoelectric transformer operating in the first and second modes have been characterized. For the first mode, the transformer has a maximum output power of 0.7 W with a temperature rise of 14 °C. For the second mode, the maximum output power of the transformer is 1.8 W with a temperature rise of 33 °C. KNN–KCT–Mn ceramics have shown to be a potential lead-free candidate to be used in high-voltage–low-current devices.

Introduction

Piezoelectric transducers have shown great promise as sensors and actuators because they are inexpensive, space efficient, lightweight, easily fabricated, and easily mounted on a variety of surfaces. With the development of fine ceramic technology, piezoelectric materials have been used for power devices such as piezoelectric transformers and ultrasonic motors. A piezoelectric transformer is a device that transforms an ac voltage or current by the piezoelectric effect at electromechanical resonance frequency. Compared with an electromagnetic transformer, a piezoelectric transformer has the following favorable characteristics: easy to be miniaturized with a large power to volume ratio; electromagnetic-noise-free; nonflammable because of no windings; higher working frequency. In the past, many types of piezoelectric transformer have been proposed and developed [1–11]. Among various types of the piezoelectric transformer, a Rosen-type piezoelectric transformer has a simple structure and high-voltage-output characteristics, which is commonly used in practical applications [1–3].

As known, $Pb(Zr,Ti)O_3$ (PZT) ceramics play a dominant role in current piezoelectric applications because of their superior piezoelectric properties. However, the use of lead-based ceramics causes serious environmental problems because of the high toxicity of lead oxide and its high vapor pressure during sintering. Therefore, there is a great need to develop lead-free piezoelectric ceramics with excellent piezoelectric properties for replacing the lead-containing ceramics in various applications. A number of lead-free piezoelectric ceramics such as alkaline niobate-based materials [12–22], $Bi_{0.5}Na_{0.5}TiO_3$-based materials [23–26], Bi-layered structure materials [27,28], tungsten bronze-type materials [29], and $BaTiO_3$-based ceramics [30] have been extensively investigated. Among them,

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$K_{0.5}Na_{0.5}NbO_3$ (abbreviated as KNN) is one of the most promising candidates for lead-free piezoelectric ceramics.

In this study, $K_{0.5}Na_{0.5}NbO_3$–$K_{5.4}Cu_{1.3}Ta_{10}O_{29}$–$MnO_2$ (KNN–KCT–Mn) ceramics with relatively high planar electromechanical coupling factor (k_p) and mechanical quality factor (Q_m) were developed. With the "hard" piezoelectric characteristics of this KNN-based ceramics, a lead-free Rosen-type piezoelectric transformer has been fabricated and characterized.

Experimental

The KNN–KCT–Mn ceramics were prepared by a conventional ceramic fabrication technique using analytical-grade metal oxides or carbonate powders. $K_{0.5}Na_{0.5}NbO_3$ and $K_{5.4}Cu_{1.3}Ta_{10}O_{29}$ powders were prepared using a solid-state reaction. The starting materials were as follows: K_2CO_3 (99.9%), Na_2CO_3 (99.8%), Nb_2O_5 (99.95%), CuO (99.9%), and Ta_2O_5 (99.9%) Desired amounts of starting materials were weighed and mixed in ethanol using zirconia balls. After drying, KNN powder was calcined at 880 °C for 6 h, and KCT powder was calcined at 950 °C for 5 h. After calcinations, 0.38 mol% $K_{5.4}Cu_{1.3}Ta_{10}O_{29}$ and 0.25 mol% MnO_2 (99.9%) were added to the calcined KNN powders. The powders were ball milled again and mixed thoroughly with a polyvinyl alcohol (PVA) binder solution for dry pressing. The disk samples of 15 mm diameter were sintered at 1,110 °C for 4 h in air. After the sintered disk samples were polished to less than 1 mm thickness, a fired-on silver paste was applied to the top and bottom surfaces of the samples as electrodes. The ceramics were poled under a dc field of 3 kV/mm at 200 °C in silicone oil for 30 min.

The microstructure of the ceramics was observed using scanning electron microscopy (Leica Stereoscan 440) A conventional Sawyer-Tower circuit was used to measure the polarization hysteresis (*P*–*E*) loop of the ceramics at 100 Hz. Piezoelectric properties of the ceramics were measured by means of the resonator method on a basis of IEEE standard using an impedance analyzer (Agilent 4294A) [31]. The piezoelectric coefficient d_{33} of the samples was measured using a d_{33} meter (ZJ-3B, China). The key properties of KNN–KCT–Mn ceramics are shown in Table 1.

Table 1 Properties of the KNN–KCT–Mn ceramics

Density ρ ($\times 10^3$ kg/m^3)	4.65
Q_m	1900
$\varepsilon_{33}^T/\varepsilon_0$ @ 1 kHz	300
$T_g\delta$ @ 1 kHz	0.003
k_p	0.40
k_{31}	0.24
d_{33} ($\times 10^{-12}$ C/N)	90
d_{31} ($\times 10^{-12}$ C/N)	–33
Poisson's ratio σ	0.27
s_{11}^E ($\times 10^{-12}$m^2/N)	6.91

A Rosen-type piezoelectric transformer, as shown in Fig. 1 (a), with a dimension of 21 mm × 6 mm × 1.2 mm was fabricated using the KNN–KCT–Mn ceramics. The approximate distributions of displacement and stress for the first mode (half-wave mode) and the second mode (full-wave mode) are plotted in Fig. 1 (b) and (c), respectively. For the first mode, when the piezoelectric transformer works, the clamping point should be in the center, while for the second mode 1/4 length and 3/4 length would be clamped due to the zero displacement at these points. The generator section of the sample was poled along the length direction under a dc field of 3 kV/mm for 30 min in silicone oil at 200 °C, while the driver section of the sample was poled along the thickness direction under a dc field of 5 kV/mm for 30 min at 120 °C.

Impedance properties of the piezoelectric transformer were measured as a function of frequency using a precision impedance analyzer (Agilent 4294A). The characteristics of the piezoelectric transformer under variable load resistance were investigated using a similar experimental setup in our previous study [32]. A pure resistive load R_L (>10 kΩ) was used. In order to minimize the effect of stray capacitance of oscilloscope on voltage gain of the transformer, the output voltage was simply measured by monitoring voltage of a 1 kΩ resistor serially connected to R_L. The temperature rise in the transformer was measured by an infrared thermometer about 1 min after applying the input voltage. The temperature rise in the transformer can be controlled properly by tuning the input voltage.

Results and discussion

Figure 2 shows a slightly constricted *P*–*E* hysteresis loop of the KNN–KCT–Mn ceramics. The remanent polarization P_r and coercive field E_c are 11.8 μC/cm^2 and 0.85 kV/mm, respectively. Compared with a pure KNN ceramic [33], the KNN–KCT–Mn ceramics has a smaller P_r and a comparable E_c. The substitutes of Cu^{2+} and Mn^{4+}/Mn^{3+} for Nb^{5+} in the B-sites of KNN result in the formation of defect dipoles by the defect ions Cu^{2+} and Mn^{4+}/Mn^{3+} (negatively charged) and O^{2-} vacancies (positively charged) [34–36]. On the basis of symmetry-conforming principle of point defects [37], the defect dipoles provide a restoring force to reverse the switched polarization upon removal of the external field. As a result, macroscopically, the ferroelectric dipoles are difficult to deviate from their original orientation due to the strong restoring force generated by

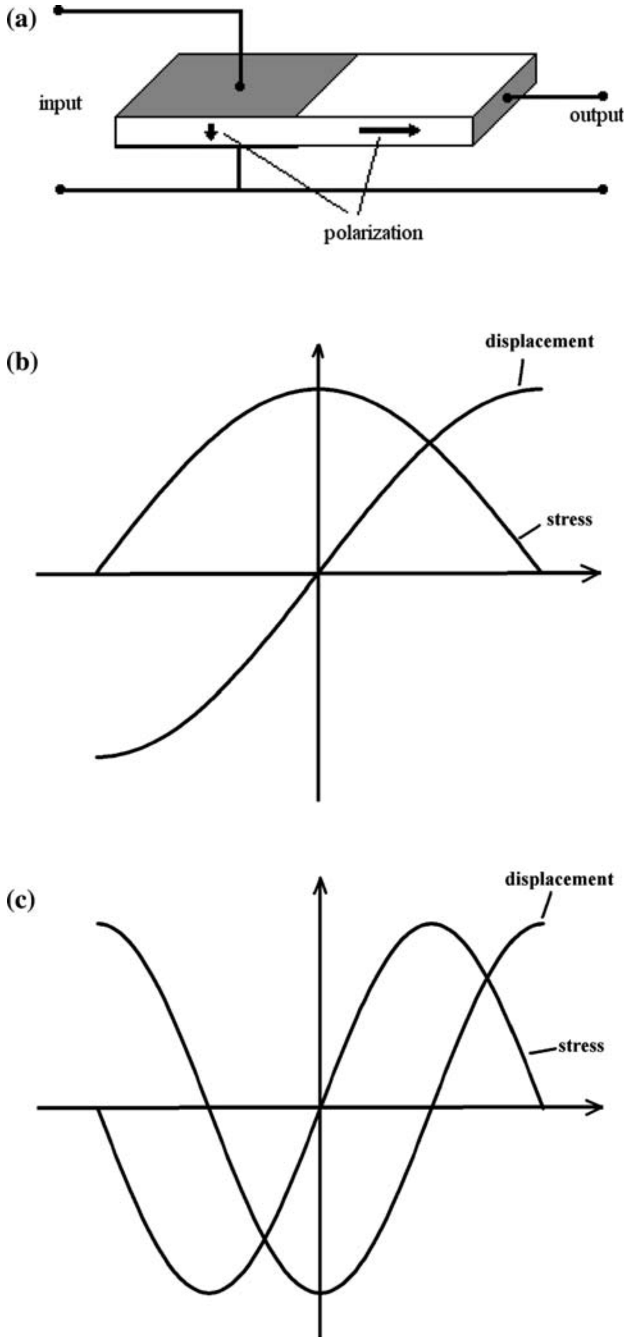


Fig. 1 A Rosen-type piezoelectric transformer: (**a**) configuration, and distribution of displacement and stress of the first mode (**b**) and the second mode (**c**)

defect dipoles. That is, defect dipoles will “pin” the motion of ferroelectric dipoles. Consequently, a constricted *P–E* loop is observed, and the excellent “hard” piezoelectric properties in KNN–Mn–KCT ceramics are obtained. A scanning electron microscopy (SEM) micrograph of the KNN–KCT–Mn ceramics is shown in Fig. 3. It can be seen that the density of ceramics is high and the grain size is small with an average 2 μm in diameter.

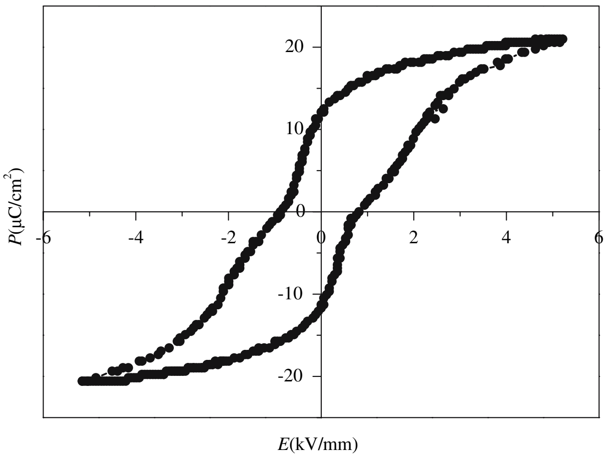


Fig. 2 *P–E* hysteresis loop of the KNN–KCT–Mn ceramics

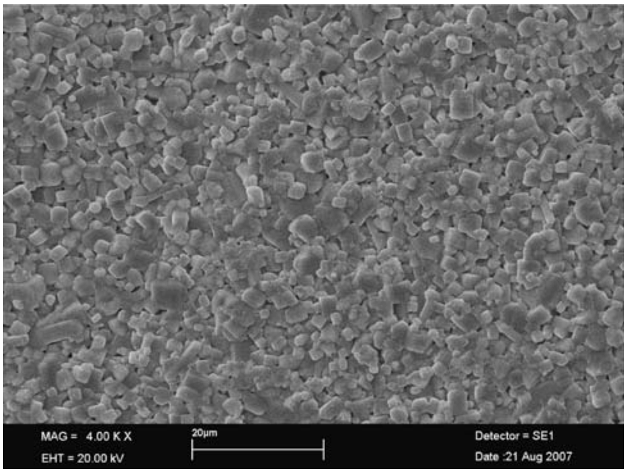


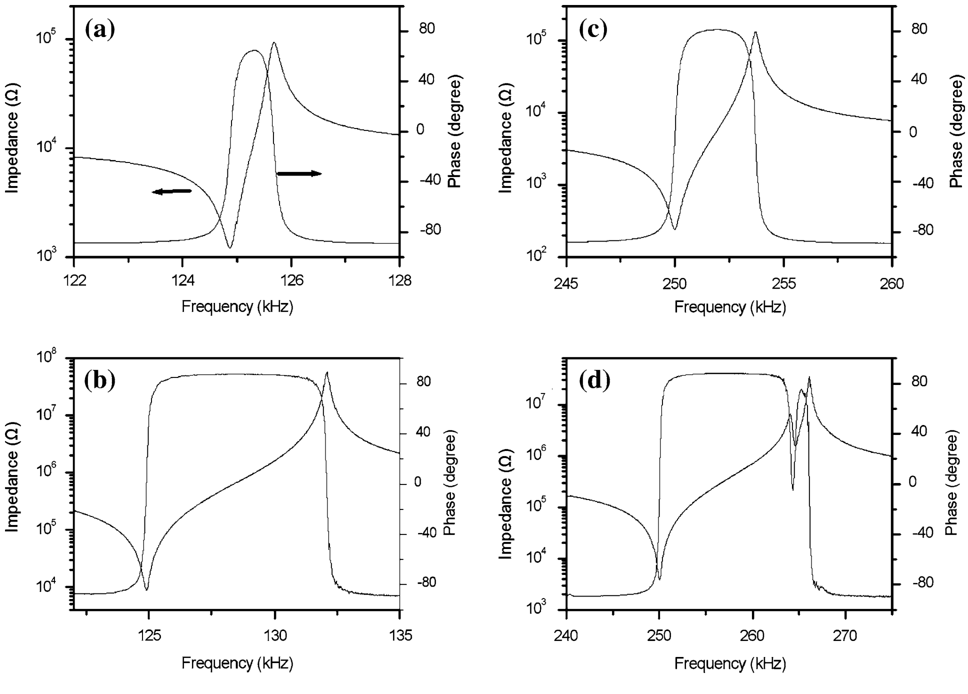
Fig. 3 SEM micrograph of the KNN–KCT–Mn ceramics

The measured impedance spectra of the KNN–KCT–Mn Rosen-type piezoelectric transformer are shown in Fig. 4. The resonances of the first mode [Fig. 4(a) and (b)] and the second mode [Fig. 4(c) and (d)] are strong and clear. The electrical equivalent circuit of piezoelectric transformers operated near the resonance frequencies can be simplified as shown in Fig. 5 [7]. The turn ratio of the transformer *N* can be calculated by

$$N = \sqrt{\frac{L_{\mathrm{mOUTPUT}}}{L_{\mathrm{mINPUT}}}} \qquad (1)$$

The equivalent circuit parameters of the transformer under different vibration modes were determined using an impedance analyzer. Each part of the transformer was measured under the condition, while the other part was short-circuited. The results are shown in Table 2. Using the Eq. 1, the *N* value of the first and second modes is 2.74 and 4.33, respectively.

Fig. 4 Impedance spectra of the KNN–KCT–Mn piezoelectric transformer near the first vibration mode [(**a**) input part, (**b**) output part], and the second vibration mode [(**c**) input part, (**d**) output part]



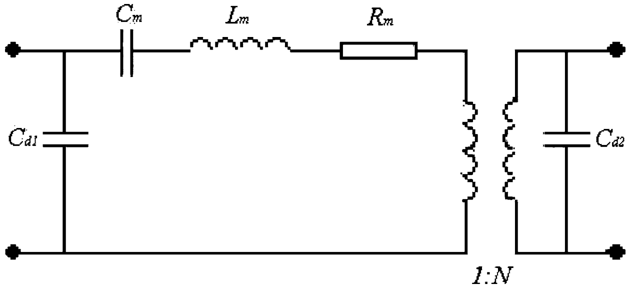


Fig. 5 Equivalent circuit of the piezoelectric transformer

Figure 6 shows plots of the voltage gain of the piezoelectric transformer in the first and second modes as a function of frequency with different resistive loads. It is seen that the maximum voltage gain of the transformer increases with resistive load. The maximum voltage gain of the piezoelectric transformer with a load resistance of 1 MΩ is 21 and 76, for the first mode and the second mode respectively. Besides the load resistance and driving frequency, the voltage gain also depends on the properties of the piezoelectric material. It is deduced that the voltage gain for a very large load resistance (open circuited) is approximately proportional to the mechanical quality factor Q_m and electromechanical coupling factors: [1]

$$V_{out}/V_{in} \propto k_{31}k_{33}Q_m(L/t), \tag{2}$$

where L and t are the length and thickness of the transformer, respectively. The main key to enlarge the voltage gain of the transformer is to increase the length/thickness ratio of the transformer, and the electromechanical coupling factors and mechanical quality factor of the piezoelectric ceramics.

It is known that the efficiency of a piezoelectric transformer attains a maximum value when the load resistance is equal to $(1/\omega C_{d2})$ where C_{d2} is the clamped capacitance of the output part of the transformer [7]. This load resistance is called a matching load. Using parameters in Table 2, the matching loads can be determined to be about 700 kΩ for the first mode, and 400 kΩ for the second mode. The relationship among the maximum output power, efficiency, temperature rise, and input voltage of the matching loaded piezoelectric transformer in the first and second modes is shown in Fig. 7. The maximum output power is defined as the maximum value of the output power with respect to the driving frequency for a given

Table 2 Parameters of the input and output parts of the piezoelectric transformer

		f_r (kHz)	f_a (kHz)	R_m (Ω)	L_m (mH)	C_m (pF)	C_d (pF)	Q_m
The first mode	Input	124.9	125.7	1220	1025	1.58	125	660
	Output	124.9	132.1	8617	7707	0.211	1.78	700
The second mode	Input	250.0	253.7	240	111.6	3.63	122	730
	Output	250.0	266.1	3686	2090	0.194	1.47	890

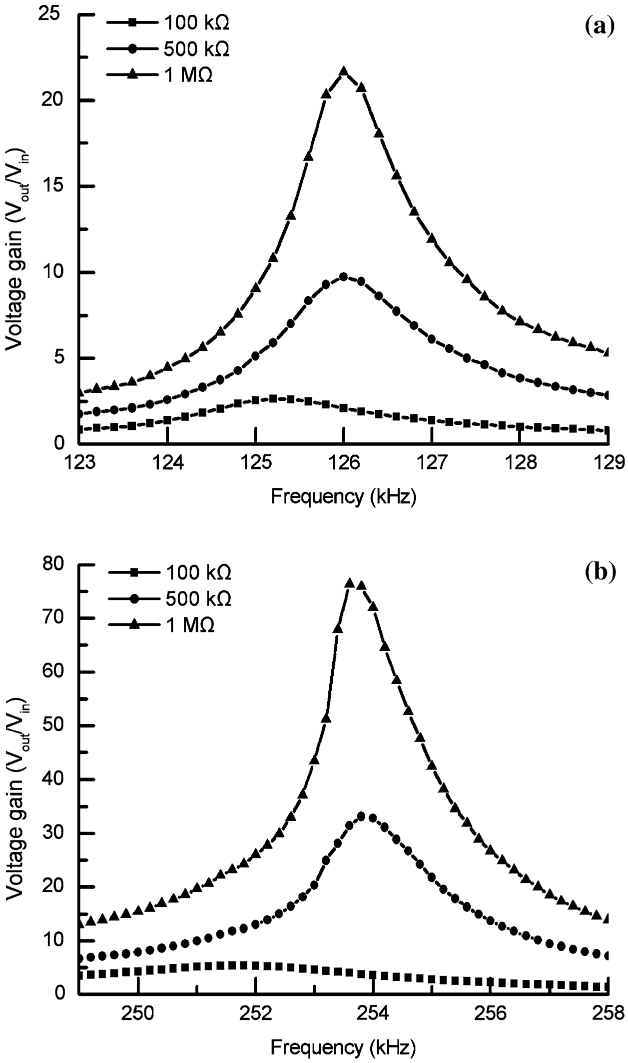


Fig. 6 Voltage gain as a function of frequency and load resistance at (**a**) the first mode, and (**b**) the second mode

input voltage. The whole surface of the transformer was scanned to obtain the maximum temperature. As shown in Fig. 7, the output power is larger for the transformer operated in the second mode for a given input voltage. For the first mode, when the input voltage is 140 V_{pp} (peak-to-peak value), the maximum output power is 0.7 W with a temperature rise of 14 °C. For the second mode, the maximum output power approaches 1.8 W with a temperature rise of 33 °C when the input voltage is 115 V_{pp}. The efficiency for both operation modes can be higher than 80%. Compared with a PZT piezoelectric transformer, the lead-free one has a lower power-to-volume ratio due to the relative weak piezoelectric performance of the lead-free element. Since the electromechanical coupling factors and the maximum vibration velocity v_{max} of the lead-free ceramics are lower than that of the PZT, the maximum output power of the lead-free transformer would be lower.

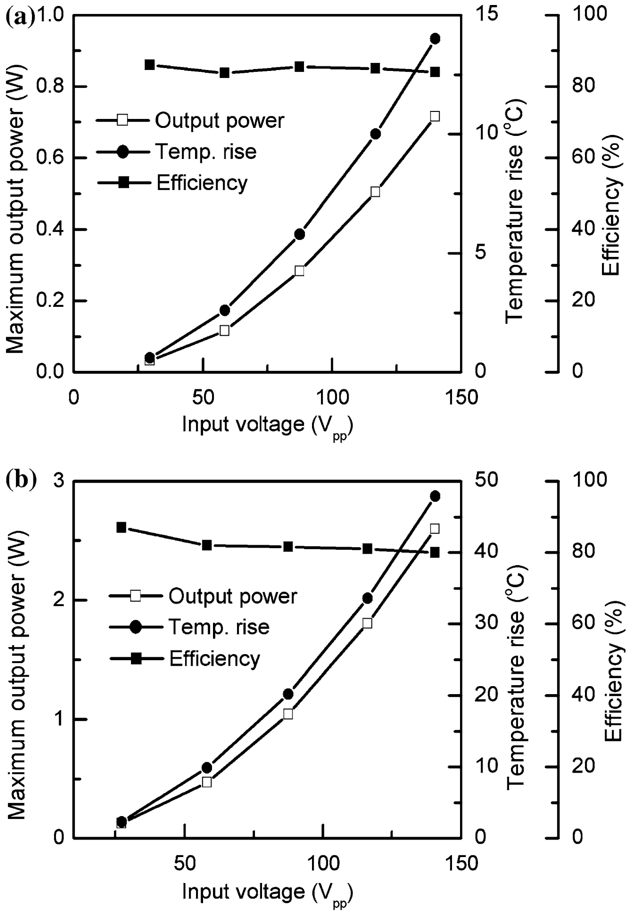


Fig. 7 Relationship among the maximum output power, efficiency, temperature rise, and input voltage of the matching loaded piezoelectric transformer in (**a**) the first mode, and (**b**) the second mode

Nevertheless, with the low-density nature of the lead-free ceramics, the lead-free transformer has a comparable power-to-weight ratio to the lead-based transformer [3].

Conclusions

Lead-free KNN–KCT–Mn ceramics have been prepared by a conventional ceramic sintering technique. The ceramics show excellent piezoelectric properties for application in power devices, and the optimum properties measured are as follows: $d_{33} = 90$ pC/N, $k_p = 0.40$, $Q_m = 1{,}900$. A Rosen-type piezoelectric transformer with a dimension of 21 mm × 6 mm × 1.2 mm was fabricated successfully using the KNN–KCT–Mn ceramics. Properties of the piezoelectric transformer operating in the first and second modes were characterized. For the first mode, the transformer has a maximum output power of 0.7 W with a temperature rise of 14 °C. For the second mode, the maximum output power of the transformer is 1.8 W with a temperature rise of 33 °C. It is shown that the

KNN–KCT–Mn transformer has potential to be used in high-voltage–low-current devices.

Acknowledgements This work was supported by the Niche Area Project (No. 1-BB95) and the Centre for Smart Materials of The Hong Kong Polytechnic University.

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