



Low temperature co-fired multilayer piezoelectric transformers for high power applications

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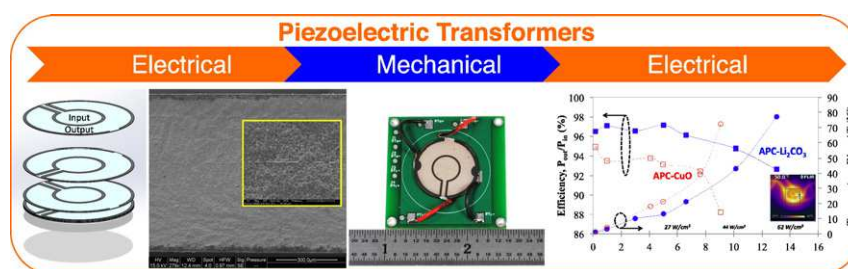
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HIGHLIGHTS

- Piezo-transformers were made competitive to legacy electromagnetics for space qualified 10 W power supplies.
- Multilayer hard-piezoceramic transformers were co-fired at or below 1000 °C.
- High efficiency (>95%) and power density (>30 W/cm³) were achieved.
- 40 W/cm³ and 60 W/cm³ power densities were achieved without cooling or heat-sink.

GRAPHICAL ABSTRACT



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ABSTRACT

Piezoelectric transformers (PT's) offer high efficiency in compact volumes compared to their electromagnetic counterparts. In particular, multilayer PT's can deliver both efficiency and higher power when they are made of hard-piezoceramics. However, hard-piezoceramics usually have high sintering temperatures (~1200 °C), which limit the inner electrode of the multilayer structure to precious metals such as silver palladium (Ag/Pd) with high Pd content or platinum (Pt). High Pd content or Pt increases device price dramatically and their electrical/thermal performances are not satisfactory for high power multilayer applications. Therefore, two compositions were developed by utilizing a commercially available hard-piezoelectric ceramic (APC 841) and sintering temperature was brought down to 1000 °C or below by keeping essential high power properties at satisfactory levels (mechanical quality factor ~1000, planar coupling coefficient > 0.5, and dielectric loss < 0.02). Then, ring-dot step-down multilayer PT's were prototyped and co-fired with Ag/Pd:90/10 electrodes accordingly. PT's were able to reach an output power density level of 30 W cm⁻³ ($P_{\text{output}}/\text{Volume}$) with >96% efficiency ($P_{\text{output}}/P_{\text{input}}$) and a 20 °C temperature rise. In addition, PT's were tested at higher output power levels and were able to generate 45 W cm⁻³ and 60 W cm⁻³ with a temperature rise of 40 °C and 80 °C, respectively.

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1. Introduction

Advancements in technology have led to more self-monitoring electronic systems with various feedback loops and sensors. These mini-systems may require different power solutions (voltage level and/or electrical signal (AC/DC)). Electromagnetic transformers (EMT's) are

the most traditional and simple solution to power management in electronics. On the other hand, they are typically the heaviest in weight and sometimes the largest component in an electronic system. Therefore, increasing the number of EMT's due to power requirements will significantly increase the volume and weight of the total system. Unfortunately, simply miniaturizing EMT's result in significant decrease in efficiency due to increased resistive losses (i.e., Joule heat).

Piezoelectric materials can convert electrical energy into mechanical energy or vice versa. They are popularly utilized in sensors, sonars, and actuators. Piezoelectric materials can also be adopted to power

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converters in special design configurations. Piezoelectric transformers (PT's) simultaneously convert energy from electrical to mechanical at the input, then mechanical to electrical at the output (i.e., primary and secondary sides). Unlike EMT's, energy conversion in PT's takes place in a solid-state nature, and therefore are very efficient and easier to miniaturize compared to EMT's [1]. In addition, in miniaturized electronic devices electromagnetic interference (EMI) plays a critical role in reliability [2]. Since PT's are EMI-free, this becomes a major advantage for PT's versus EMT's. Overall, PT's can combine high efficiencies in compact volumes without EMI, which is crucial for industries such as aerospace and portable devices.

PT's attracted many researchers after it was introduced in the 1950's by Rosen as "the Rosen Type transformer" [3]. Rosen type transformers can convert low voltages to high voltages (step-up) typically with low currents [4–7]. Step-down PT's can convert high voltages to low voltages typically with high currents. Ring-dot designs are popularly used as step-down PT's [8–12]. Even though both types have been widely studied, the only notable commercialization for PT's was for LCD backlight inverters in portable devices industry [13]. In addition, there have been some efforts to increase the power output (power density) level of PT's by utilizing the multilayer technology [4,12,14]. Therefore, multilayer technology is proved to be extremely critical to improve the power densities of the PT's and make them superior to EMT's in small volume applications. So far, power density levels (P_{output}/V) up to 40 W cm^{-3} have been reported in the literature for optimized PT designs [15].

Piezoelectric transformers demand the use of hard-piezoelectric ceramics (hard-piezoceramics), which have low losses (i.e. mechanical and dielectric). Since hard-piezoceramics usually require high sintering temperatures (up to 1300°C), metallization (electroding and connectivity) used in fabrication of hard-type (co-fired) multilayer piezoceramics are usually silver palladium (Ag/Pd) with high Pd content or platinum (Pt) due to its capability of withstanding these high processing temperatures. However, Pd and Pt are not only expensive but also have poor electrical/thermal conductivity that degrades the device performance. Reducing sintering temperature would enable multilayer piezoceramics industry to shift from these expensive metallizations to lower cost pure silver or silver palladium (lower Pd content), and even to extremely low cost base metals such as copper (Cu) with excellent electrical/thermal conduction characteristic. On the contrary, base metals oxidize in ambient and high temperature sintering conditions and require reduced atmosphere sintering conditions. Hence, if base metal co-firing is desired, hard-piezoceramic composition needs to be carefully selected considering the thermodynamic relationship between the piezoceramic and the co-firing metallization under the reduced atmosphere sintering conditions. By addressing these issues, pricing disadvantage of PT's over EMT's can be eliminated with significantly improved performance enabling broader commercial applications.

Most of the research on low temperature sintering of hard-piezoceramics has been carried out for lead-based and/or lead-zirconate-titanate ($\text{Pb}(\text{Zr,Ti})\text{O}_3$:[PZT])-based compositions due to this system's wide range of usage among piezoelectric applications. The critical design of a hard-piezoceramic involves an acceptor substitution mostly on the octahedral B-site of the piezoceramic (e.g., PZT), thus replacing the Zr^{4+} and/or Ti^{4+} cations with acceptors $\text{Fe}^{+2,3}$, $\text{Co}^{+2,3}$, Sb^{+3} , and $\text{Mn}^{+2,3}$. The formulations for air-fired hard-PZT are well understood and successfully applied to various high power piezoelectric applications such as sonars, ultrasonic motors, and piezoelectric transformers.

The classical approach to reduce the sintering temperature is to introduce flux materials with low melting temperatures to ceramic compositions. Metal oxides (e.g. MnO [16], CuO [17], and ZnO [18]), carbonates (e.g. Li_2CO_3) [19], glasses [20], and perovskite structures [21] can be utilized in conjunction with binary [19] or ternary [22] PZT-based hard-piezoceramic compositions. The main challenge in this approach is to minimize the degradation in material properties while attempting to reduce the sintering temperature. Therefore, selection of the base system,

along with flux materials and fine compositional doping materials are vital to achieve the desired material properties at low temperatures.

Recently, Ahn et al. developed a low temperature hard-piezoceramic composition based on a commercially available piezoceramic (APC 841 + CuO + ZnO) [18]. The results were promising, but the composition was not further applied to any of the co-fired multilayer high power applications. In this study, the same composition was produced along with an alternative (i.e., APC 841 + Li_2CO_3 + ZnO) as CuO was replaced with Li_2CO_3 because Li^+ ions have a higher potential to create more oxygen vacancies and lower the material losses by stabilizing the domain walls compared to Cu^{2+} ions. In addition, CuO can lead to a complicated thermodynamic relationship in the future studies with Cu co-firing (i.e. PZT-CuO/Cu).

Target application was chosen as ring-dot step-down multilayer piezoelectric transformer due to its simplicity in design, fabrication, and its ability to demonstrate high power potential of the hard-piezoceramic, which can also be correlated to its performance in other high power applications.

2. Experimental approach

2.1. Bulk sample preparation

A commercially available MnO_2 - and Nb_2O_5 -modified $\text{Pb}(\text{Zr,Ti})\text{O}_3$ (APC 841, APC Int'l, Mackeyville, PA, USA) was used as the base hard-piezoceramic composition. Metal oxides (CuO , ZnO , and PbO) and carbonates (Li_2CO_3) with purities $>99.9\%$ were mixed according to the formula APC 841 + 0.5 wt% PbO + 1.1 wt% ZnO + 0.2 wt% CuO or Li_2CO_3 for 24 h in Nalgene jars with ethanol and yttria stabilized zirconia (YSZ) milling media. Then, dried powder was sieved through a mesh with $106 \mu\text{m}$ opening and mixed with 2 wt% Paraloid in acetone solution. After mixing via mortar and pestle, powder was sieved again and then uniaxially pressed into disk shape pellets under 450 MPa pressure. Binder burnout was carried out at a 3°C min^{-1} ramp rate with soaking pellets for 2 h at 300°C and 4 h at 550°C . Pellets were sintered depending on the composition's sintering temperature range, which varied between 850 and 1050°C . Pellets were soaked for 2 h at the particular peak temperature with the ramp rate of 5°C min^{-1} . Ceramic disks were polished and lapped after sintering. Final sample dimensions were around $11 \times 1 \text{ mm}$ ($D \times t$). Silver (DuPont 6160) electrodes were printed on to top and bottom surfaces manually and then fired at 850°C for 10 min. A poling field of 3 kV mm^{-1} was applied for 20 min in silicone oil bath at 120°C to achieve uniform polarization within the ceramics.

2.2. Multilayer-LTCC prototyping

Green tapes were prepared from polyvinyl-butylal (PVB)-based slurries. The optimized slurry recipe consisted of PVB (Type BM-S, Sekisui Co. Ltd.) binder, plasticizer (G-260®, Sekisui Co. Ltd.), dispersant (blown menhaden fish oil, Z-3, Tape Casting Warehouse, Inc.), and ethanol (Et-OH) and methyl-ethyl-ketone (MEK) as solvents. First, fish oil, hard-PZT powder, Et-OH, and MEK were mixed for 24 h according to the weight ratio 0.77:0.01:0.11:0.11. Then, PVB, G-260, Et-OH, and MEK were added according to the 0.29:0.11:0.30:0.30 weight ratio and mixed for 24 h. The slurry mixture was placed on a slow mill to remove the entrapped air bubbles for 4 h before casting. Slurries were cast on a 0.003" thick Mylar® film then dried and cut into square pieces. Electrode configurations were screen printed by using 8 wt% hard-PZT powder added Ag/Pd:90/10 buried electrodes (BE901052, Heraeus). Printed and dummy/blank layers were stacked 90° alternatively considering the cast direction after trimming the unnecessary parts of the cut pieces. Stacked green tapes were pressed lightly in a uniaxial press at 55°C to improve handling of the devices before lamination. Stacks were then laminated at 70°C under 3000 psi for 20 min and ring-dot design transformers were punched out of the stacked squares. Binder burnout (BBO) occurred under ambient conditions with a slow heating rate (0.5

$^{\circ}\text{C min}^{-1}$) from 20°C up to 500°C . BBO profile was estimated from the thermogravimetric analysis (TGA) of the ring-dot transformer pieces. Binder-free green tapes were sintered for 2 h at temperatures taken from the bulk sintering studies. Terminals of the transformers were polished to expose the electrodes and then terminated with ESL 599-G termination electrode at 560°C for 20 min. Wires were soldered on terminals and then the same poling procedure as bulk ceramics was followed.

2.3. Material and electrical characterization

Bulk density was measured with Archimedes method in deionized (DI) water. X-ray diffraction (XRD) patterns were collected with PANalytical Empyrean X-ray diffractometer via $\text{Cu K}\alpha = 0.154 \text{ nm}$. Scanning electron micrographs were imaged with FEI Quanta 200 Environmental SEM. Thermogravimetric analyses (TGA's) were made with TGA 2050 for simple heating/cooling cycle and Q600 SDT for complicated heating/cooling cycles (TA Instruments). Dielectric loss and capacitance measurements were made at 1 kHz and 1 V with an LCR meter (HP-4272A). Piezoelectric constant (d_{33}) was measured at 100 Hz with a Berlincourt type d_{33} meter (Piezotest, PM300). Planar electromechanical coupling coefficient (k_p) and mechanical quality factor (Q_m) were calculated according to the impedance spectroscopy data, which was recorded by an impedance analyzer (HP-4294A) with $0.5 V_{\text{rms}}$ input. Q_m was calculated with 3 dB up/down method around the resonance and k_p was calculated with the following equation: $k_p^2 = \{0.395[f_r / (f_{ar} - f_r)] + 0.574\}^{-1}$.

3. Results & discussion

3.1. Material characterization

Sintering optimization for modified APC 841 ceramics was carried out between 850 and 1050°C (Fig. 1). A separate sintering optimization was also carried out for the base APC 841 ceramics and optimum sintering temperature was found around 1280°C when sintered for 2 h. Except the sole Li_2CO_3 flux addition, both CuO - ZnO and Li_2CO_3 - ZnO modified ceramics were able to reach high density levels compared to the unmodified ceramics sintered at high temperature (1280°C). Solely Li_2CO_3 flux addition to the base APC 841 ceramic was not able to bring the sintering temperature down to the desired levels ($\sim 1000^{\circ}\text{C}$). When ZnO was added as the additional flux material, the ceramic composition was sinterable within the target range. This result reflects the findings in the earlier paper on the same base composition, where CuO flux addition

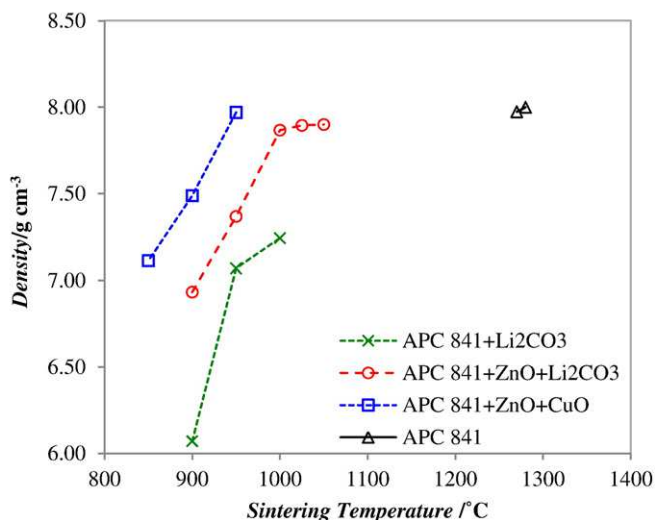


Fig. 1. Density as a function of sintering temperature for APC 841 and modified APC 841 piezoelectric ceramics for sintering in ambient conditions for 2 h.

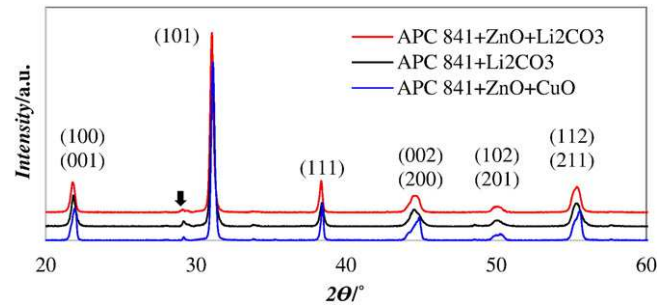


Fig. 2. X-ray diffraction (XRD) analysis of modified APC 841 ceramics after sintering at 900°C for 2 h in ambient conditions.

was more effective when it was used with ZnO [18]. Compared to the base APC 841 composition, piezoceramics could be sintered around 900°C and 1000°C for CuO - ZnO and Li_2CO_3 - ZnO modifications, respectively. As a result, this temperature range opened a large window for various inner electrode materials.

X-ray diffraction spectra of modified APC 841 ceramics (Fig. 2) showed the perovskite PZT phase with a negligible amount of a secondary phase ($\downarrow \text{Pb}_2\text{Nb}_2\text{O}_7$) [17]. Since the base APC 841 powder was already modified with Nb_2O_5 and MnO_2 , this secondary phase could be traced back to the manufacturer. In addition, this phase was also observed in the APC 841 ceramics sintered at 1280°C , which is not shown in Fig. 2. This extra phase was more pronounced in the composition without ZnO addition (APC 841 + Li_2CO_3). The decrease in $\text{Pb}_2\text{Nb}_2\text{O}_7$ phase can be related to a possible $\text{Pb}(\text{Zn}_x\text{Nb}_{1-x})\text{O}_3$ phase formation with ZnO addition to the modified APC 841 compositions.

3.2. Electromechanical & dielectric characterization

Considering a higher crystallization ratio and improved grain growth at higher temperatures, electromechanical properties were improved for both candidate materials with the increased sintering temperature (Fig. 3). CuO -modified piezoceramics were able to possess satisfactory electromechanical properties at lower sintering temperatures compared to the piezoceramics modified with Li_2CO_3 . This difference is clearer when the electromechanical properties are compared for the piezoceramics sintered at the same temperature (950°C). This variance can be directly correlated with the low density of Li_2CO_3 -modified piezoceramics, which was shown in Fig. 1. However, when sintering temperature was further increased for Li_2CO_3 -modified piezoceramics, this difference disappeared and then they even showed a significant improvement in the electromechanical coupling coefficient (k_p) while maintaining mechanical

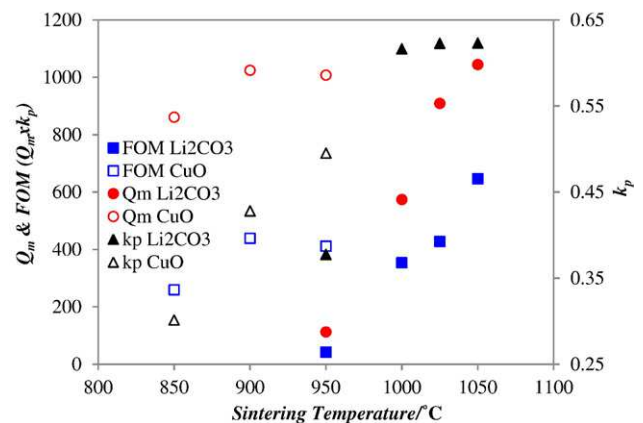


Fig. 3. Key electromechanical properties of CuO -modified ($\square$, 850 – 950°C) and Li_2CO_3 -modified ($\blacktriangle$, 950 – 1050°C) APC 841 piezoceramics as functions of sintering temperature.

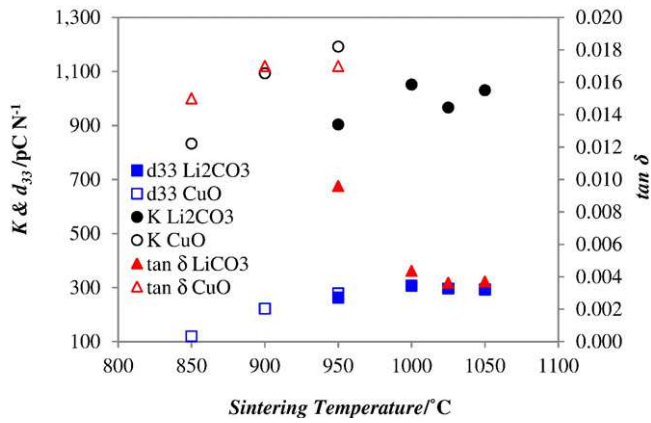


Fig. 4. Key dielectric and piezoelectric properties of CuO-modified ($\square, \Delta$, 850–950 °C) and Li_2CO_3 -modified ($\blacksquare, \blacktriangle$, 950–1050 °C) APC 841 piezoceramics as functions of sintering temperature.

quality factor (Q_m) at a similar level to that of CuO-modified piezoceramics. Thus, Li_2CO_3 -modified piezoceramics showed a higher value for the figure of merit ($\text{FOM} = Q_m \times k_p$) for high power applications when sintered at suitable temperatures.

Similar improved behavior was only observed for the real piezoelectric and dielectric properties for increased sintering temperatures (Fig. 4). Dielectric loss ($\tan \delta$) was slightly increased with increasing temperature for CuO-modified piezoceramics while maintaining a significantly higher level compared to Li_2CO_3 -modified piezoceramics. Still, $\tan \delta$ was not quite high for CuO-modified ceramics but this rather unexpected behavior of $\tan \delta$ could not be further speculated with current results. Compared to the large difference in electromechanical properties (Fig. 3), the piezoelectric constant (d_{33}) was almost the same for piezoceramics sintered at 950 °C and showed slight improvement for Li_2CO_3 -modified piezoceramics sintered at higher temperatures. The difference was more reflective in the dielectric properties. In addition to the characteristically low $\tan \delta$, Li_2CO_3 -modified piezoceramics possessed lower dielectric constant (K) compared to CuO-modified piezoceramics.

The performance of CuO-modified piezoceramics were similar to that of Ahn et al. when sintered at 950 °C. However, considering overall material properties and multilayer design (i.e., electrode materials), the optimum sintering temperatures for the candidate materials were chosen as 900 °C and 1000 °C for CuO-modified and Li_2CO_3 -modified APC 841 ceramics, respectively.

3.3. Piezoelectric transformer design & testing

Ring-dot design was selected for the piezoelectric transformer (PT) application due to the simplicity in design and manufacturing. This type of transformers usually operates in the radial mode (k_p) and brings high voltages to lower voltages with relatively high currents. Step-down ratio (gain) is mainly dictated by the inner (dot) and outer (ring)

electrode designs, which identify the capacitances of the input and output terminals, respectively. Therefore, step-down, and multilayer co-fired piezoelectric transformers were prototyped with both candidate materials (Fig. 5). A conventional PT design was used based on our previous works; however, the design was not finalized by doing a fine design optimization.

Piezoelectric transformers (PT's) showed dense microstructures without delamination and ceramic-electrode interface were uniform and continuous (Fig. 6a–b). Electrode and ceramic layer thicknesses of PT's were around 3 μm and 120 μm , respectively. Active layers varied between 6 and 9 but 7-layer devices were chosen for high power characterization to avoid possible mode couplings around operating frequencies between the resonances. Final dimensions of PT's were around $19 \times 0.8 \text{ mm}$ (OD $\times$ t) (Fig. 6c). In addition, the inner dot (input terminal) and ring (output terminal) diameters were around 8 mm and 18 mm, respectively.

Low-power electrical characterizations (i.e., impedance and LCR) provided important data to predict device characteristics before the high power characterization. Output (ring) and input (dot) terminals were measured separately and to reduce static effects one terminal was short circuited while the other one was being measured for all low power measurements. Besides the capacitance due to the difference in electrode areas, the major difference between the output and input was the larger electromechanical coupling coefficient, which can be clearly seen with a larger bandwidth for the output (ring) terminal in Fig. 7. This can be a natural result related to the vibration mode requirements for the radial mode. Output (ring) terminal has a larger diameter compared to the input (dot) terminal and therefore radial coupling coefficient (k_p) is larger for this terminal.

Table 1 summarizes material properties based on the initial electrical characterizations. Assuming the piezoelectric transformers (PT's) had relatively similar dimensions, resonance frequency shifted to lower frequencies for Li_2CO_3 -modified APC 841 PT's, which can be directly correlated to their slightly lower density (Fig. 1). In addition, Li_2CO_3 -modified APC 841 PT's also showed higher coupling coefficients (k_p) than CuO-modified APC 841 PT's similar to the results in bulk piezoceramics (Fig. 3). Correlation of bulk and multilayer properties continued for the dielectric loss ($\tan \delta$) with Li_2CO_3 -modified APC 841 PT's having almost an order lower value compared to CuO-modified APC 841 PT's. Moreover, capacitance values were also rather similar as a reflection of similar dielectric constant (K) levels in Fig. 4 for both groups. Impedance at resonance (Z_r) was quite low and similar for both CuO- and Li_2CO_3 -modified APC 841 PT's.

Piezoelectric transformers (PT's) were tested around their matching loads (10 Ω) when driven by sinusoidal (AC) input signal at operating frequencies between resonance (f_r) and anti-resonance (f_{ar}) around fundamental mode, where the power efficiency is maximized ($P_{\text{out}}/P_{\text{in}}$). In addition, devices were suspended in air during the measurements to avoid heat transfer via conduction along any contact surfaces. The measurements were taken when devices reached specific output power (P_{out}) levels (e.g., 1 W and 5 W) and typically with 20–40 °C increase

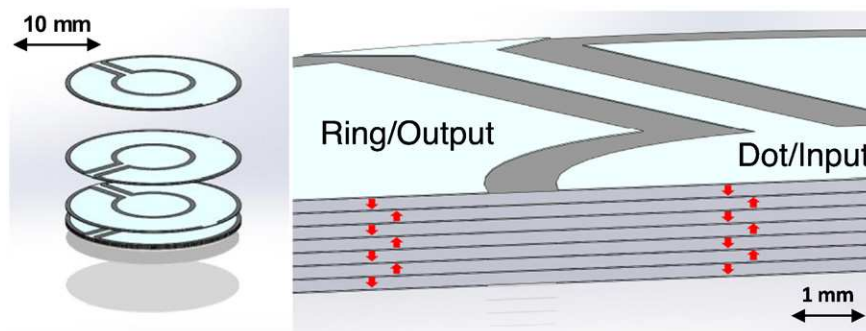


Fig. 5. Stacking layout showing the 90° alternation of the layers (left) and cross-sectional view showing polarization direction for each layer (right) for the piezoelectric transformers (PT's).

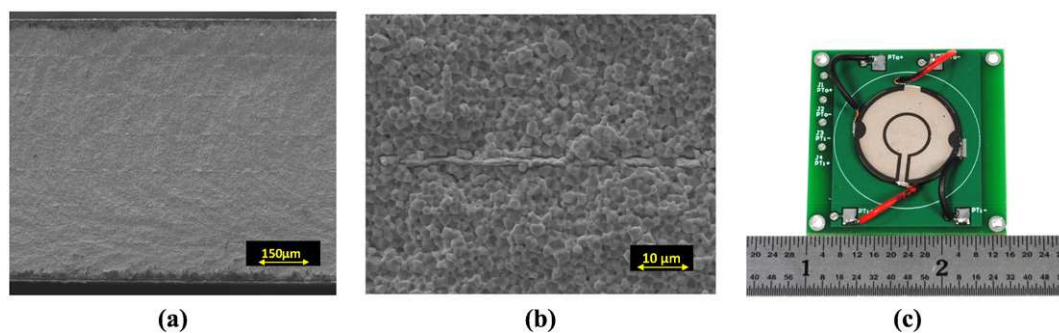


Fig. 6. Cross-sectional scanning electron microscopy (SEM) micrographs showing the continuous electrode-piezoceramic (a) layers and (b) interfaces from a crack surface, and (c) an image of a multilayer piezoelectric transformer (PT).

in their temperatures due to increased losses. The measurements were taken when the device was stabilized for the specific power/temperature level. In order to maintain the input current at resonance, a signal generator (Agilent 33220A) was connected to a high-speed power amplifier (NF HSA4014). Input/output currents and voltages were measured with non-contact current and in-contact voltage probes, respectively. Probes were calibrated before each device to minimize reading errors. Input power, output power, and efficiency were calculated and monitored via an oscilloscope (Tektronix DPO7104). Then, the results were averaged after measuring at least five devices.

Overall, Li_2CO_3 -modified APC 841 multilayer piezoelectric transformers (PT's) showed better performance than CuO-modified APC 841 PT's (Fig. 8). This behavior reflected the higher figure of merit (FOM) observed for the bulk piezoceramics. When devices reached $\Delta T = 20^\circ\text{C}$ (the maximum vibration velocity point), CuO- and Li_2CO_3 -modified PT's were able to output around 5 W with 93% efficiency and 7 W with 96% efficiency, respectively. As a rule of thumb, output power increases with the increased volume of piezoceramic used. Therefore, instead of total power, power density is used to represent the capability of the PT's. Thus, at $\Delta T = 20^\circ\text{C}$ CuO- and Li_2CO_3 -modified PT's were able to reach 23 W cm^{-3} and 30 W cm^{-3} , respectively. At higher input voltage levels, Li_2CO_3 -modified PT's could even reach 45 W cm^{-3} and almost 60 W cm^{-3} in a stable continuous vibration mode. Not only these low temperature co-fired PT's showed comparable power density levels to the PT's fired/co-fired at high temperatures but also, they were able to surpass these levels when they were driven at slightly elevated temperatures. In order to verify the operating temperature limits, the input voltage was increased until the PT's reached $T = 100^\circ\text{C}$. PT's showed similar performance as in the initial power test, which proved that both PT's were reliable even after elevated driving conditions to obtain the desired output power level. Moreover, output power density of the PT's can be further enhanced with proper cooling methods (e.g., heat sink) typical

to electronic components [23,24] and/or special design configurations [25], which will be investigated for the reported transformers in future studies.

Several piezoelectric transformers were made in our other efforts parallel to this study. All of our efforts were based on the same candidate piezoceramic systems (i.e., CuO-APC 814 and Li_2CO_3 -APC 841). In these efforts effects of various binder systems and co-firing electrodes were tested. According to these results, Ag/Pd:95/05 co-fired piezoelectric transformers (PT's) provided improved results compared to Ag/Pd:90/10 co-firing. Since everything else was the same except the metallization, this result could be correlated with lower resistivity of the 95/05 metallization compared to 90/10, which was provided in the manufacturer's datasheet.

Since CuO-modified APC 841 piezoceramics have lower sintering temperature than Li_2CO_3 -modified APC 841 piezoceramics, they can be co-fired with Ag/Pd:95/05 electrodes. Based on our previous studies, this change will automatically improve the high power performance of these devices and make them more comparable to Li_2CO_3 -modified APC 841 piezoelectric transformers co-fired with 90/10 electrodes. Even though, the CuO-modified APC 841 PT's initially showed slightly lower efficiency, their efficiency can be improved by switching the co-firing electrode to 95/05. Moreover, this change can also lower the cost of the PT's by replacing palladium with a lower cost silver.

4. Summary & conclusions

Two piezoceramic compositions were developed from a commercially available hard-piezoceramic (APC 841). When 1.1 wt% ZnO was incorporated with 0.2 wt% CuO or 0.2 wt% Li_2CO_3 , sintering temperature of the APC 841-based piezoceramic composition was decreased to 1000°C or below without creating any significant secondary phases.

Both piezoceramic compositions showed high power application potential based on their low power electrical characterization results. Mechanical quality factor (Q_m) levels were around 1000, electromechanical coupling factors (k_p) were between 0.45 and 0.65, and piezoelectric coefficient (d_{33}) levels were around $280\text{--}300\text{ pC N}^{-1}$ range. Li_2CO_3 -modified APC 841 piezoceramics showed lower dielectric loss ($\tan \delta = 0.4\%$) whereas CuO-modified piezoceramics showed significantly higher dielectric loss ($\tan \delta = 1.7\%$). When overall properties were compared, Li_2CO_3 -modified piezoceramics showed more promising properties regarding high power application potential.

Table 1
Characteristic material properties for CuO- and Li_2CO_3 -modified APC 841 multilayer piezoelectric transformers.

		f_r/kHz	f_{ar}/kHz	k_p	Z_r/Ω	$\tan \delta$	C/nF
CuO	Dot (Input)	116	122	0.36	1.7	0.017	35
	Ring (Output)	116	123	0.39	0.2	0.018	120
Li_2CO_3	Dot (Input)	110	118	0.41	1.4	0.008	39
	Ring (Output)	110	119	0.44	0.3	0.008	137

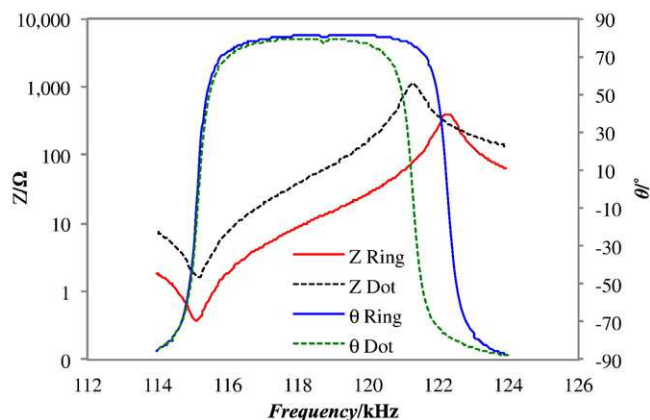


Fig. 7. Impedance (Z) and phase (θ) spectra at the input (dot) and output (ring) terminals of a piezoelectric transformer around the fundamental mode.

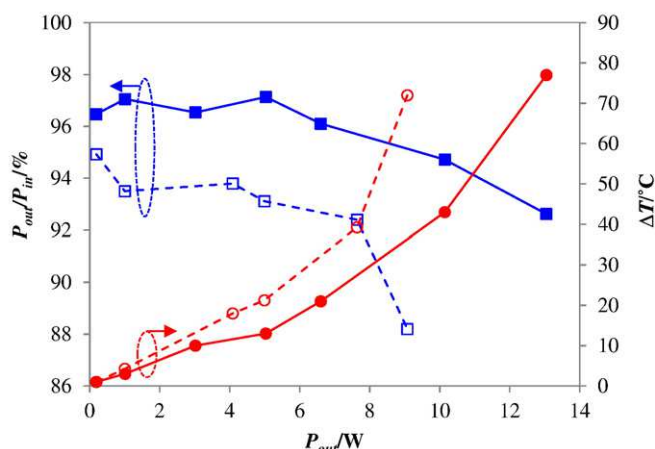


Fig. 8. High power performance in the form of efficiency (P_{out}/P_{in}) and temperature rise (ΔT) as functions of output power (P_{out}) for CuO- ($\square$) and Li_2CO_3 -modified ($\bullet$) APC 841 multilayer piezoelectric transformers in continuous driving mode around their matching impedance.

Both piezoceramic compositions were utilized in multilayer piezoelectric transformers (PT's) with 90/10:Ag/Pd co-firing. CuO- and Li_2CO_3 -modified APC 841 PT's were able to reach power density levels of 23 W cm^{-3} and 30 W cm^{-3} , respectively with a 20°C temperature rise and high efficiency ($\geq 93\%$) at their impedance matching loads. PT's were further tested for higher output power density levels. When the temperature of Li_2CO_3 -modified APC 841 PT's reached 60°C and 100°C , they could output 45 W cm^{-3} and 60 W cm^{-3} , respectively. The results showed that with a suitable heat sink/cooling design, power density of these transformers can be improved further to enable broader commercial use.

Hard-piezoceramics can be co-fired below their sintering temperature by adding suitable flux materials (i.e. CuO $\sim 900^\circ\text{C}$ or $\text{Li}_2\text{CO}_3 \sim 1000^\circ\text{C}$). The reduction in sintering temperature opened a large window for alternative co-firing electrode materials and Ag/Pd:90/10 was selected to demonstrate the capabilities of these commercially available hard-piezoceramic compositions. In this study, PT's co-fired at low temperatures ($\leq 1000^\circ\text{C}$) showed improved performance (i.e. power density) compared to the power density levels available in the literature. This is very promising to reduce the PT's prices by eliminating Pt or high Pd content Ag/Pd electrodes from co-firing. Furthermore, the sintering temperatures in this study are suitable for base metal electrode (e.g., Cu) co-firing, which will further reduce the materials cost and improve the performance and hence, enable PT's to be competitive to electromagnetic transformers (EMT's) in terms of cost and performance.

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