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Multilayer piezoelectric ceramic transformer with low temperature sintering

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The low-fired high performance piezoelectric ceramics used for multilayer piezoelectric transformer were investigated. Based on the transient liquid phase sintering mechanism, by doping suitable eutectic additives and optimizing processing, the sintering temperature of the quaternary system piezoelectric ceramics with high piezoelectric properties could be lower to about 960–1000°C. The low-temperature sintering multilayer piezoelectric transformer (MPT) has been developed. Some characteristics of MPT were systemically studied. The measurements include the frequency response of input impedance, frequency response of phase difference between input voltage and current, frequency shifting with load, input impedance changing with load, phase difference between input voltage and current shifting with load, and phase difference between input voltage and vibration velocity. The vibration modes and resonance characters of MPT were measured by a Laser Doppler Scanning Vibrometer. Several kinds of MPT with high voltage step-up ratio, high power density, high transfer efficiency and low cost have been industrially produced and commercialized. It reveals a broad application prospect for back-light power of liquid crystal display and piezo-ionizer etc.

1. Introduction

Low-firing multilayer piezoelectric transformer (MPT) was studied in Beijing Tsinghua University on the 1980's. This kind of MPT has high voltage step-up ratio, low driving voltage, small size, and low cost. Its voltage step-up ratio is ten times higher than that of conventional single-layer transformer. As known, the sintering temperature of normal piezoelectric ceramics is high up to about 1200–1300°C. In order to decrease the consumption of precious metal in internal electrode, the low sintering temperature PZT-based piezoelectric ceramics with high performance have been investigated systematically in Tsinghua University. Several kinds of low-firing high performance piezoelectric ceramics including binary, ternary and quaternary system compositions have been developed respectively. They can be sintered at 820–1000°C and obtained with excellent properties. A new kind of quaternary system piezoelectric ceramics PMN-PZN-PZT can be satisfactorily used for low firing MPT. Recent years, with the rapid development of the electronic information technology which provides a huge market requirement for electronic devices with the increasing of surface mount technology (SMT), which provides more and more conventional components have to be replaced by multilayer chip-type surface mount devices (SMD). Based on this background the chip-type MPT has attracted more attention and interested by many researchers and users. A new type piezoelectric inverter used for the back-light power of liquid crystal display in portable computer and piezo-ionizer has been developed. The MPT and its inverters have many advantages, such as thin shape, small size, high transfer efficiency, anti-interfere for electro-magnetic. The MPT and inverters have been produced in industrial scale and commercialized by Xi'an Konghong Company in China.

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2. Low-firing piezoelectric ceramics with high performance

The chemical grade and analytical grade raw materials Pb_3O_4, TiO_2, ZrO_2, Nb_2O_5, ZnO, Li_2CO_3, CdO, MnO_2, $SrCO_3$ were used and powders were prepared by conventional oxide synthesis processing, the samples that were formed into discs having a diameter of 15 mm and thickness of 1mm under the pressure of about 100 Mpa were coated with silver paste and fired. After firing samples were polarized by a DC electric field at 4 kV/mm in 120°C silicon oil. The dielectric and piezoelectric properties were measured by HP4194.

The composition of quaternary system PMN-PZN-PZT ceramics is given as follow:

$$x\mathrm{Pb}(\mathrm{Mn}_{1/3}\mathrm{Nb}_{2/3})\mathrm{O}_3 - y\mathrm{Pb}(\mathrm{Zn}_{1/3}\mathrm{Nb}_{2/3})\mathrm{O}_3 - z\mathrm{Pb}(\mathrm{Z}_{\mathrm{ru}}\mathrm{T}_{\mathrm{iv}})\mathrm{O}_3 + \mathrm{add.w\%}.$$

where $x+y+z = 1$; $0 \leq x \leq 0.20$, $0 \leq y \leq 0.35$, $0.50 \leq z \leq 0.90$, $u = 0.52$, $v = 0.48$, $0 \leq w \leq 10$. The technical route of low temperature sintering is the transition liquid phase sintering, low eutectic melting additives as initial phase can promote the sintering in the early and middle stages of sintering and as a final phase can form solid solution to enter the lattice and modify the properties of ceramics. The suitable amount doping can be reacted with PbO to form an eutectic phase and advantage to lower sintering temperature. Both benefit of low firing and high performance ceramics can be obtained. The properties of PMN-PZN-PZT are as follow. $K_p = 0.60$, $d_{33} = 300$ pC/N, $\varepsilon_{33}^T/\varepsilon_0 = 1050$, $Q_m = 1500$, $tg\delta \leq 50\times10^{-4}$, sintered at about 960°C–1000°C. This kind of piezoelectric ceramics is satisfied used for MPT.

3. Some characteristics of multilayer piezoelectric transformer

The MPT with Rosen type and central driving type has been studied respectively. The properties of MPT with central driving are listed in the Table I.

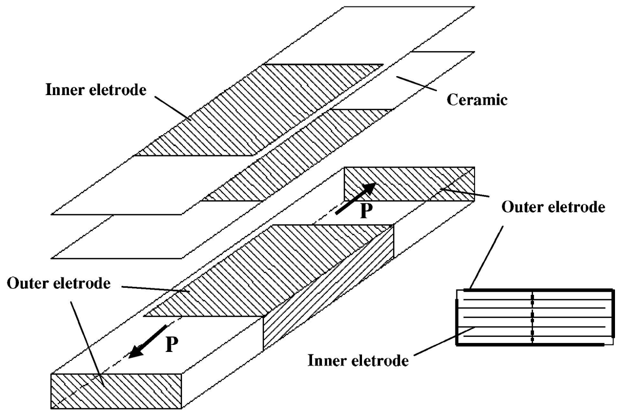


Figure 1 Schematic configuration of MPT.

How to suppress the temperature rise of MPT during operating is one of important technique requirements for practice application, because the transfer efficiency decreases when increasing temperature. Many factors can influence the temperature variation of MPT. The composition of ceramics with low loss, high mechanical quality factor, and low resonance impedance are desired for MPT application. The fabrication processing of MPT is also very important during the sintering of MPT. The densification mismatch behavior between metallic internal electrodes and ceramic layers can induce the residual internal stress and micro-cracks. The induced defects at the interface between electrode and ceramics severely deteriorate the mechanical and electrical properties. Especially, during vibration span, the defects at the interface can generate a dynamic internal stress field and result in the temperature rise. In the present study, the internal electrode (Ag/Pd = 85/15) can be cofired with PMN-PZN-PZT ceramics sintered at about 960–1000°C.

The maximum surface temperature rise is less than 20°C at rated output power. It is indicated that the low sintering temperature MPT with high performance can be obtained. It has been used in back-light power for portable computer. These kinds of MPT and their back-

TABLE I The properties of MPT with central driving

	Specification[a]			
	1503	2505	3006	4509
Resonant frequency (λ/2, kHz)	110	70	54	36
Voltage step-up ratio (load = 100 kΩ)	45	60	70	90
Output power (W)	1.0	3.0	4.0	8.0
Transfer efficiency (%)	≥95	≥95	≥95	≥95
Dimensions (l × w × h) (mm^3)	1.6	2.6	2.6	5.0
Layer thickness (mm) × layer numbers	0.15 × 13	0.20 × 17	0.20 × 17	0.25 × 15
Sintering Temperature (°C)	≤1000	≤1000	≤1000	≤1000

[a]Specification 1503, 2505, 3006, 4509 represent the size of length and width of MPT. Their length and width are 15 mm and 3 mm, 25 mm and 5 mm, 30 mm and 6 mm, 45 mm and 9 mm respectively.

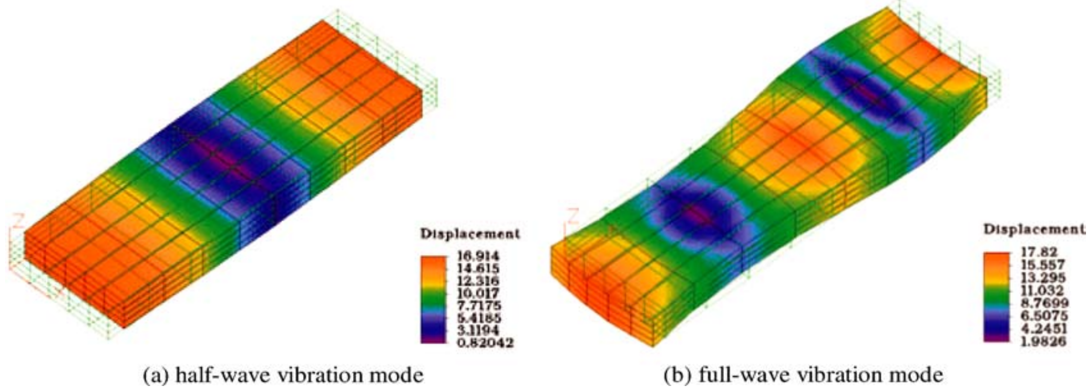


Figure 2 Finite element analysis for the vibration mode of MPT.

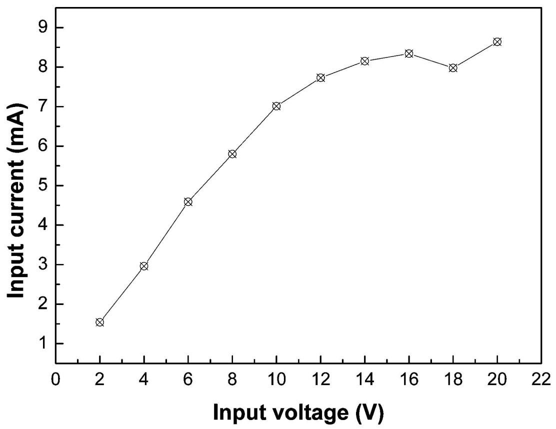


Figure 3 Relationship between input voltage and current for measuring MPT.

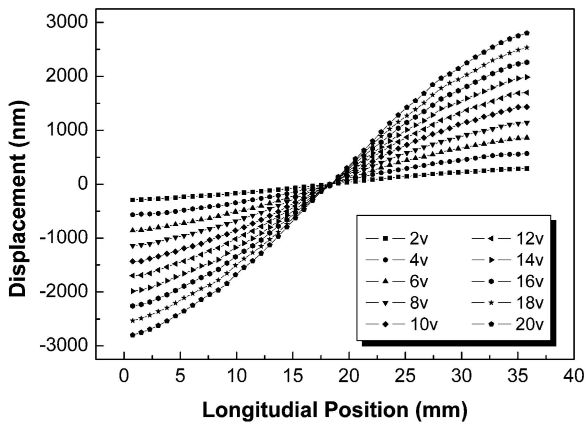


Figure 4 Displacement distribution along the length direction for MPT.

light power and piezo-ionizer have been produced in industrial scale and commercialized by Xi'an Konghong Company in China.

4. Some of resonance characteristics for MPT

The configuration of MPT is shown in Fig. 1. The monolithic multilayer structure contains 17 layers of 0.20 mm in thickness. There is an input electrode strip at the center of the transformer and symmetrical output terminal electrodes at both ends. The mechanical vibration along longitudinal direction can be generated by the electromechanical coupling factors k_{31} and k_{33} under alternating input voltage. For half wave vibration, a nodal line without any vibration appears at its center and such symmetric vibration results in two identical step-up voltages at two output terminals.

Finite Element Analysis (FEA) is a very useful method to simulate the vibration mode of the MPT when subjected to a driving voltage. The symmetric harmonic vibration of the MPT was confirmed by using the FEA method, as shown in Fig. 2. It can be seen that at different harmonic frequency, the MPT vibrates with different vibra-

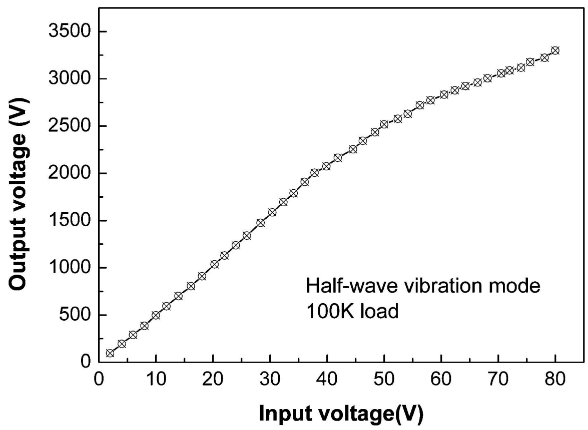


Figure 5 Relationship between input voltage and output voltage for measuring MPT with 100 kΩ load.

tion mode, the half-wave mode and the full-wave mode in this case. The maximum displacement occurs at the end of MPT. The nodal position located at the central of MPT for half-wave vibration mode.

Furthermore, the actual vibration modal shapes, including micro vibration displacement, were experimentally

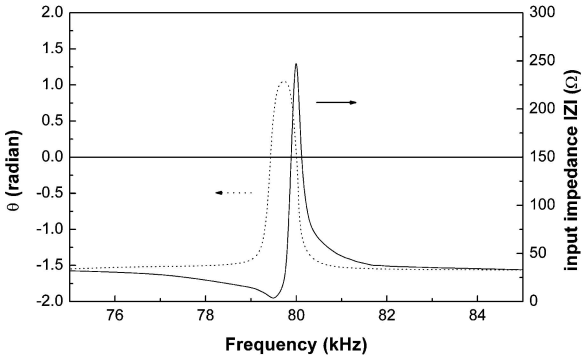


Figure 6 Input impedance and phase difference between input voltage and input current with relation to frequency.

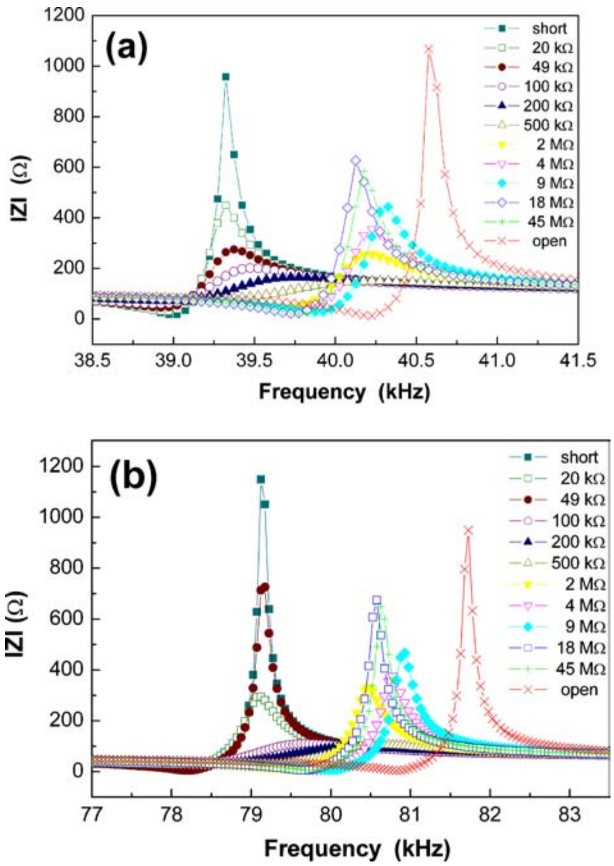


Figure 7 Shifts of input impedance as a function of load at (a) half-wave and (b) full-wave resonant vibration mode, respectively.

measured by using a Laser Doppler Scanning measurement system. Fig. 3 shows the input current value as a function of applied voltage.

The relationship between displacement distribution and input voltage is shown in Fig. 4. It can be seen that the largest displacement occurs at the end of MPT. The displacement increases with increasing of input voltage. Fig. 5 shows the transformation characteristics of the MPT. The output voltage exhibits excellent linear dependence on the input voltage up to 40 V, over which the transformation ratio falls down with the input voltage.

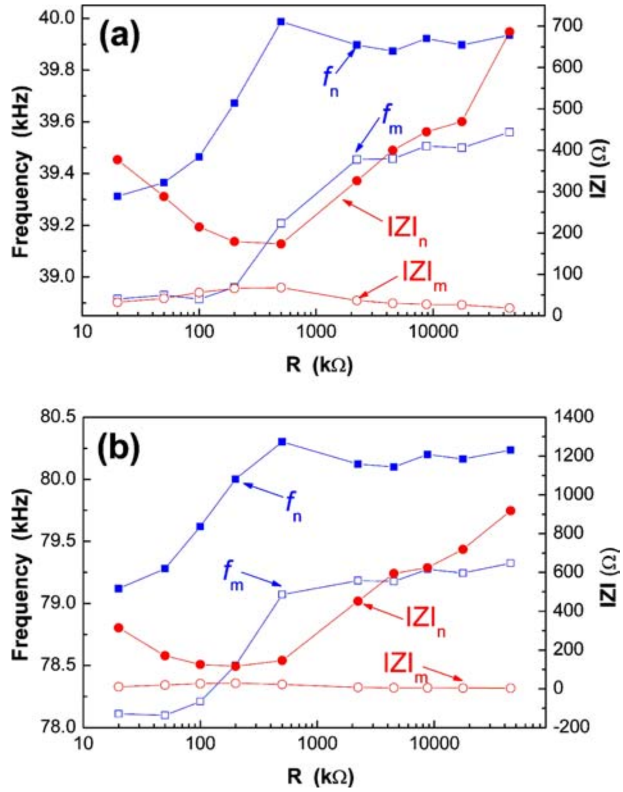


Figure 8 Shifts of frequency and input impedance as a function of load at (a) half-wave and (b) full-wave vibration mode.

Fig. 6 shows the input impedance and phase difference between input voltage and input current with relation to the frequency. It can be seen that at resonant and antiresonant state, the phase difference is zero and the input impedance reveals pure resistance behavior. Between the two frequencies, the input impedance shows inductance. At off-resonant state, the input impedance shows obvious capacitance characteristics.

The influences of load at the output end of MPT on the input impedance were studied. Fig. 7a and b shows the shifts of input impedance as a function of load at half-wave and full-wave vibration modes respectively. The experimental results show that input impedance depends strongly on loads. When the load increases from short to open circuit, the peak location of input impedance moves toward higher frequency and its magnitude undergoes sharp variation within the two values according to the states of short and open circuit.

Fig. 8a and b shows the variation tendency of input impedance and frequency as a function of load at half-wave and full-wave vibration mode, respectively. The parameters with the subscription "m" refer to values at the local minimal input impedance, while the "n" refers to val-

TABLE II The specification of piezoelectric ceramic transformers

Item	MPT2505	MPT3006	MPT3006	MPT3507	MPT4007	MPT4008	MPT4509
Output power (W)	2.5	3.5	4.0	4.5	5.0	6.5	8.5
Rated output power (W)	2.0	3.0	3.5	4.0	4.5	6.0	8.0
Resonant frequency (kHz)	70 ± 2.0	55 ± 2.0	55 ± 2.0	47 ± 2.0	41 ± 2.0	41 ± 2.0	36.5 ± 2.0
Voltage set-up ratio (at the resonant frequency)	60 ± 10%	65 ± 10%	70 ± 10%	80 ± 10%	67 ± 10%	70 ± 10%	72 ± 10%
Efficiency (at the resonant frequency)	≥ 90%	≥ 90%	≥ 90%	≥ 90%	≥ 90%	≥ 90%	≥ 90%
Input capacitance (nf @ 1 kHz, 1 Vrms)	65 ± 10%	115 ± 10%	135 ± 10%	205 ± 10%	185 ± 10%	190 ± 10%	310 ± 10%
Input voltage (max,Vpp)	28	30	30	30	30	35	35
Input current (max, mArms)	500	600	650	800	700	800	1300
Output voltage (max, Vop)	1500	1700	1800	1900	2000	2300	2600
Output current (max, mArms)	5.5	6.0	7.0	7.3	7.5	8.0	9.2
Temperature rise (max, °C)	25	25	25	25	25	25	25
Operating temperature range (°C)	−10 ∼ 80	−10 ∼ 80	−10 ∼ 80	−10 ∼ 80	−10 ∼ 80	−10 ∼ 80	−10 ∼ 80

ues at local maximal input impedance. The state indicated by "m" refers to the resonant state, while that indicated by "n" refers to the anti-resonant state. An interesting phenomenon is observed about input impedance, $|Z|_m$ varies slightly with loads, while $|Z|_n$ varies with loads strongly, which gives some useful information on the matching impedance of power supply to MPT.

Fig. 9a and b shows the variation of phase difference between input voltage and current as a function of load at half-wave and full-wave vibration modes.

It can be seen that the peaks of phase difference between input voltage and current show symmetric features along the vertical axial-frequency axial. Both the locations of the symmetrical axial and magnitude of the curves change with the load as well as input impedance. The symmetrical axial shifts from low frequency to high frequency as the output circuit changes from short to open, the magnitude of phase difference also shows obviously changes with loads. This phenomenon seems useful to the analysis of operating state of MPT and thus improvement of operating efficiency of MPT.

The vibration velocity of end part of MPT was measured directly by using an optic fiber interferometer with the type of OFV3000/502. Fig. 10 shows the phase difference between vibration velocity and input voltage decreases with increasing of input voltage for half-wave and full-wave resonance. It can be seen that the phase difference between velocity and input voltage decreases gradually with increasing of input voltage, the phase difference is close to 180° and 0° for open and short circuit respectively.

The low-fired MPT have been industrially produced by Xi'an Konghong Company in China. Table II summaries several kinds of the specification of piezoelectric ceramic transformers.

The multilayer piezoelectric transformers have been used in back light power for LCD. Table III lists the specification of piezo-inverter produced by Konghong Company. The KHI series of piezo-inverter can meet the technical requirements of the wide screen LCD, which include low input voltage and high starting voltage, low power dissipation and high brightness, due to the advantages of high voltage step up ratio, small size, high transferring efficiency, and high safety stability.

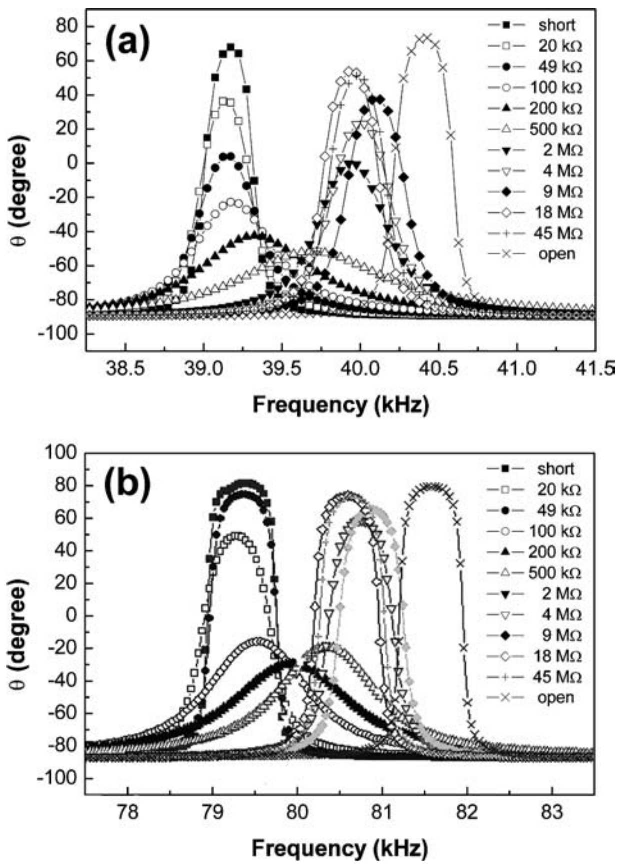
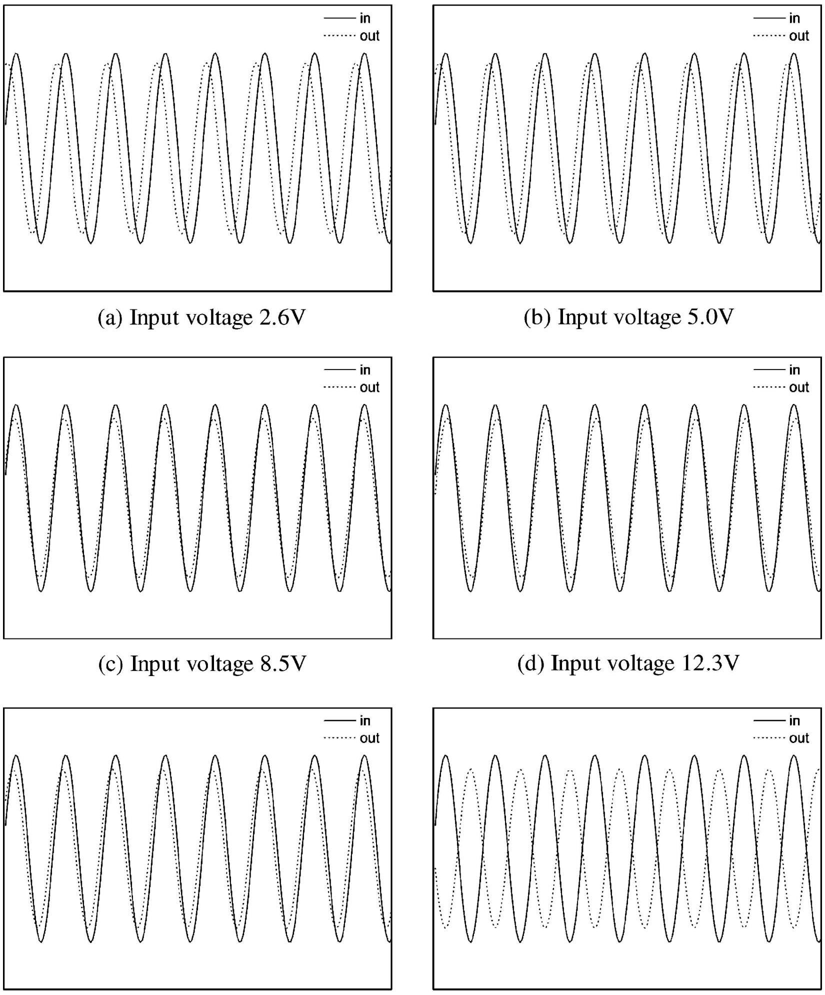


Figure 9 Shifts of phase difference as a function of load at (a) half-wave and (b) full-wave vibration mode, respectively.

TABLE III The specification of piezoelectric inverter

Item	KHI0520	KHI0530	KHI0540	KHI1230	KHI1240	KHI1280	KHI1216	KHI1224	KHI1264
Input voltage (V)	4.5–5.5	4.5–5.5	4.8–5.5	8–18	9–18	10–14	10.8–13	10.8–13	11.4–12
Input current (mA)	340	840	1000	280	360	750	1550	2300	~7500
ON/OFF voltage (V)	1.5–5	1.5–5	1.2–5	1.5–5	1.5–5	1.5–5	1.5–5	1.5–5	1.5–5
Dimming voltage (V)	0–5	0–5	0–5	0–5	0–5	0–3	0–3	0–4	0–3
Output voltage (V)	290	660	730	530	650	650	750	667	1170
Lamp current (mA)	5.0	5.5	6.0	5.0	6.0	6.0	6.0	6.0	4.5
Number of CCFL	1 × 2W	1 × 3W	1 × 4W	1 × 3W	1 × 4W	2 × 4W	4 × 4W	6 × 4W	16 × 4W
Size (mm×mm×mm)	73 × 15.5 × 5.0	73 × 15.5×5.0	73 × 15.5×5.0	110 × 11.7×5.5	95 ×15 × 5.5	137 ×22 × 5.5	160 ×33 × 5.5	180 ×60 × 7.0	320 ×120 × 5.5



(a) Input voltage 2.6V
(b) Input voltage 5.0V
(c) Input voltage 8.5V
(d) Input voltage 12.3V
(e) Input voltage 7.36V (short)
(f) Input voltage 6.18V (open)

Figure 10 Phase difference between input voltage and end vibration velocity of MPT at full-wave resonance.

5. Summary

PMN-PZN-PZT piezoelectric ceramics doped with suitable eutectic additives, by transient liquid phase sintering, the sintering temperature can be lowered to 960°C–1000°C. This kind of hard type quarternary system piezoelectric ceramics has been used for multilayer piezoelectric ceramic transformer (MPT). The shifts of input impedance and phase difference between input voltage and current as a function of load were investigated. It is found that impedance depends strongly on load. The variation of input impedance and phase difference between input voltage and input current with frequency were also studied. The vibration mode of MPT was tested and analyzed by Laser Doppler Scanning Vibrometer. The phase difference between input voltage and vibration velocity of MPT was studied. All of these investigations on resonant characteristics of MPT are very important and useful for their applications, especially to the design of driving circuit and to the optimum of operating conditions. A series of MPTs has been used for back-light power of LCD and piezo-ionizer etc. It reveals abroad application prospect.

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