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A plate-shaped high power-density piezoelectric transformer with dual outputs

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Abstract

In this study, a high power-density dual-output piezoelectric transformer is proposed and experimentally investigated. This transformer consists of a lead zirconate titanate (PZT) ceramic plate with a size of 30 mm × 5 mm × 1 mm. It has a high mechanical quality factor Q_m and high electromechanical coupling coefficient k_{eff}. The PZT ceramic plate is poled along the width direction. The electrodes of input and output parts are on the top and bottom surfaces of the ceramic plate and separated by narrow gaps. Lead wires are pressed on the electrodes by a proper elastic force. At a temperature rise lower than 20 °C, the piezoelectric transformer has a maximum output power density of 52.7 W/cm^3 with an efficiency of 88%. The maximum efficiency of this piezoelectric transformer is 95%. Voltage gains larger than one and smaller than one are obtained in one transformer. By using a parallel combination of the two outputs of the proposed transformer, a higher output power density of 57.3 W/cm^3 can be achieved at the temperature rise lower than 20 °C.

Keywords: Piezoelectric transformer; High power density; Dual outputs; Thickness shear vibration mode

1. Introduction

Piezoelectric transformers convert the largeness of an ac voltage by the ultrasonic vibration of a piezoelectric material. Compared to the electromagnetic transformers, they have many favorable merits such as low profile, high power to volume ratio, no winding, non-inflammability and electromagnetic noise free-operation. Since the Rosen type transformer [1], many piezoelectric transformers have been proposed and developed [2–9]. However, up to now, the piezoelectric transformers are mainly used to generate high voltage for the cold cathode fluorescent lamps in notebook computers. The maximum output power density in these transformers is typically less than 30 W/cm^3. In many modern applications, for example, the power supplies for portable equipment, there is however a strong need for low-voltage transformers with miniaturized structures. It is known that there are two feasible ways to reduce the size of a piezoelectric transformer further: (i) to increase the power density of the piezoelectric transformer; and (ii) to manage several different outputs by one piezoelectric transformer. These lead to the demand for a new type of piezoelectric transformer which not only has high power density, but also can manage several different outputs.

In this study, to widen the application range of piezoelectric transformers, a high power-density piezoelectric transformer with dual outputs was proposed and developed for low-voltage applications. It operates at the thickness shear vibration mode and exhibits a maximum power density of 52.7 W/cm^3 with an efficiency of 88%.

2. Construction and principle

Fig. 1 shows the construction and dimensions of the proposed piezoelectric transformer operating at the thickness shear vibration mode. This transformer consists of a lead zirconate titanate (PZT) ceramic plate with a size of 30 mm × 5 mm × 1 mm. It has a high mechanical quality factor Q_m and high electromechanical coupling coefficient k_{eff}. The PZT ceramic plate is poled along the width direction. The electrodes of input and output parts are on the top and bottom surfaces of the ceramic plate and separated by the narrow insulating gaps. The electrode areas of the input, output 1 and 2 are 30, 45 and 75 mm^2, respectively. The relevant properties of the PZT ceramic material are shown in Table 1.

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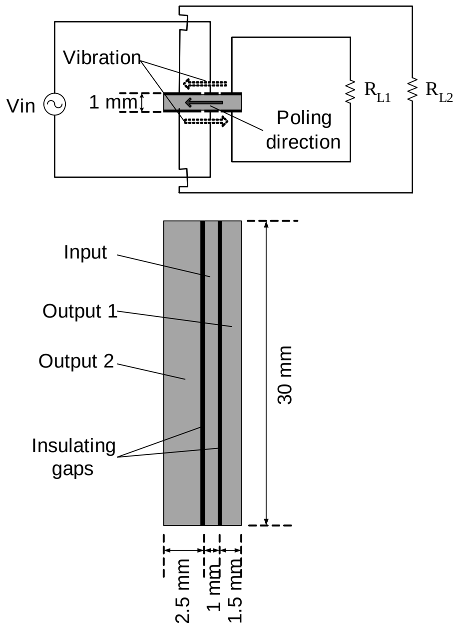

Fig. 1. Rectangular plate-shaped piezoelectric transformer operating at the thickness shear vibration mode with dual outputs.

A rectangular plate structure can effectively decrease the temperature rise of the transformer, which is beneficial to increasing the maximum power density of the transformer. The reason is that the heat dissipation ability of the transformer increases with increasing the ratio of perimeter to area of the cross section of the transformer [10]. Thickness shear mode is used in the proposed transformer because it has the largest electromechanical coupling factor of the commonly used vibration modes for most piezoelectric materials.

Fig. 2 shows the connection of the lead wires of the fabricated piezoelectric transformer with dual outputs. The lead wires with proper elasticity were chosen to keep the connection stable. By this connection, the maximum operating temperature of the transformer can be increased. Conventionally, the connection between the lead wires and electrodes of a piezoelectric transformer is realized by soldering. When the transformer operates at a large vibration, the local temperature at the solder points of the transformer may be very high. If this temperature approaches to the melting-point of the solder, the solder points fall off the electrodes. By the connection shown in Fig. 2, the above problem is avoided.

Table 1
Relevant property constants of the PZT material

Properties	Value
Dielectric constant $\varepsilon_{11}/\varepsilon_0$	1590
Electromechanical coupling factor k_{15}	0.70
Piezoelectric coefficient d_{15} (10^{-12} C/N)	510
Curie point (°C)	315
Density (10^3 kg/m^3)	7.8
Frequency constant N_{15} (mm Hz)	960
Mechanical quality factor Q_m	2500

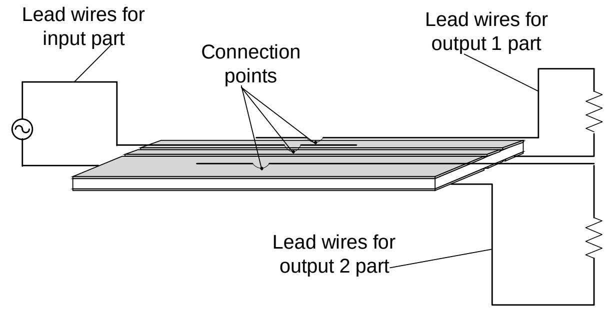

Fig. 2. Connection of the lead wires of the fabricated piezoelectric transformer.

So the maximum operating temperature of the transformer can be raised. This increases the maximum output power of the transformer.

3. Experimental setup

The characteristics of the piezoelectric transformer were measured by the experimental setup shown in Fig. 3. The transformer was driven by an ac voltage generated by a function generator and amplified by a high speed power amplifier. R_{L1} and R_{L2} are pure resisters. It is known that the efficiency of a piezoelectric transformer attains a maximum value when the load resistance is equal to the impedance of the output part. This load is called the matching load. In this study, R_{L1} and R_{L2} are the matching loads corresponding to the output 1 and 2, respectively. For the transformer proposed in this study, $R_{L1} = 350\,\Omega$ and $R_{L2} = 240\,\Omega$. The voltage, current and power of the input and output were measured by oscilloscopes. The highest temperature in the surface of the transformer was measured by an infrared thermometer about one minute after applying the input voltage. Also, the temperature rise of the transformer was kept below 20 °C in these experiments, which was controlled by properly tuning the amplitude of the input voltage.

4. Results and discussion

The parameters of the input or output parts of the proposed piezoelectric transformer (PT) were measured when the other parts were all short circuited. Table 2 shows the

Table 2
Parameters of the input and outputs of the proposed transformer

	f_r (MHz)	f_a (MHz)	S (mm^2)	Q_m	γ
Input	1.036	1.070	30	227.8	15.2
Output	1.036	1.095	120	183.2	8.8
Output 1	1.045	1.090	45	307.9	11.8
Output 2	1.036	1.124	75	180	5.9

f_r and f_a are the resonance and anti-resonance frequencies, respectively, S the electrode area, Q_m the mechanical quality factor, and γ the capacitance ratio.

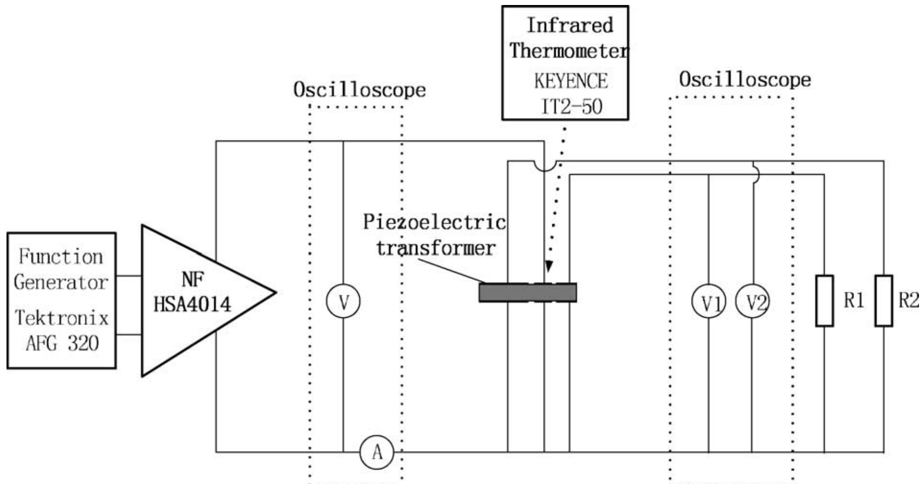

Fig. 3. Experimental setup for measuring the characteristics of the piezoelectric transformer.

measured equivalent circuit parameters of the input and the output parts of the PT. HP4194A impedance analyzer was used in the measurement. It is seen that, for the output parts, the capacitance ratio γ decreases when the electrode area increases, and the mechanical quality factor Q_m decreases as γ decreases. The reason is that, with the decrease of the capacitance ratio γ, the vibration of the ceramic material increases for a given input, and therefore the internal loss increases. Theoretically, the maximum power density $(P/V)_{max}$ can be approximately expressed as [7]

$$\left(\frac{P}{V}\right)_{max} \propto k_{eff}^2 v_{max}^2 f \tag{1}$$

in which k_{eff} is the electromechanical coupling coefficient, v_{max} is the maximum vibration velocity which is limited by the maximum temperature, and f is the driving frequency. Also, we have

$$k_{eff}^2 = \frac{1}{1+\gamma} \tag{2}$$

Therefore, the proposed piezoelectric transformer is expected to have a high power density because of the high operating frequency (over 1 MHz) and the relatively low capacitance ratio γ.

Fig. 4 shows the measured impedance characteristic of the input part of the piezoelectric transformer with matching loads. Compared with the data in Table 2, the resonance and anti-resonance frequencies of the PT all increase greatly when they have matching loads. The frequency range, in which the input part of the PT has a small $|Z|$ and a phase angle close to 0, is chosen as the optimum driving frequency range of the PT. The reason is that the vibration of the PT is stronger at the frequencies with small $|Z|$ than at other frequencies, and the efficiency is high at the frequencies where the phase angle near to 0.

Fig. 5 shows the voltage gains versus driving frequency of output 1 and 2 at their matching loads of 350 and 240 Ω. It is seen that the voltage gain varies with the driving frequency. It is larger than 1.0 for output 1 and less than 1.0 for output 2. Thus, this transformer can convert the input voltage into two different output voltages. One is step-up and another is step-down. In practical applications, in order to attain specific output voltages, one may adjust the electrode areas of the input and output parts and control the

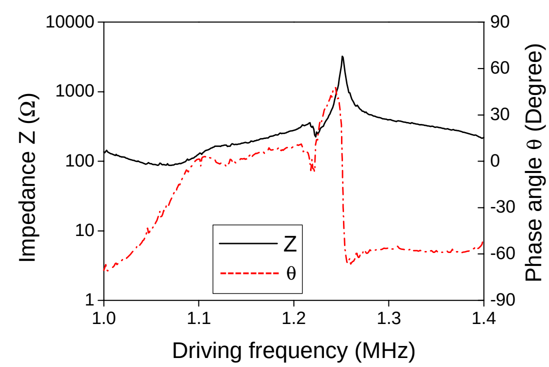

Fig. 4. Measured impedance of the input part of the piezoelectric transformer with matching loads.

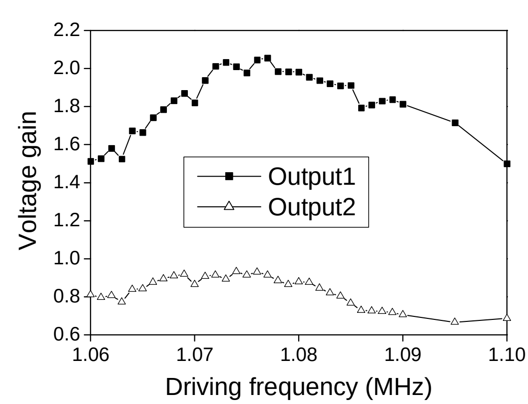

Fig. 5. Voltage gain vs. driving frequency of the proposed piezoelectric transformer with matching loads.

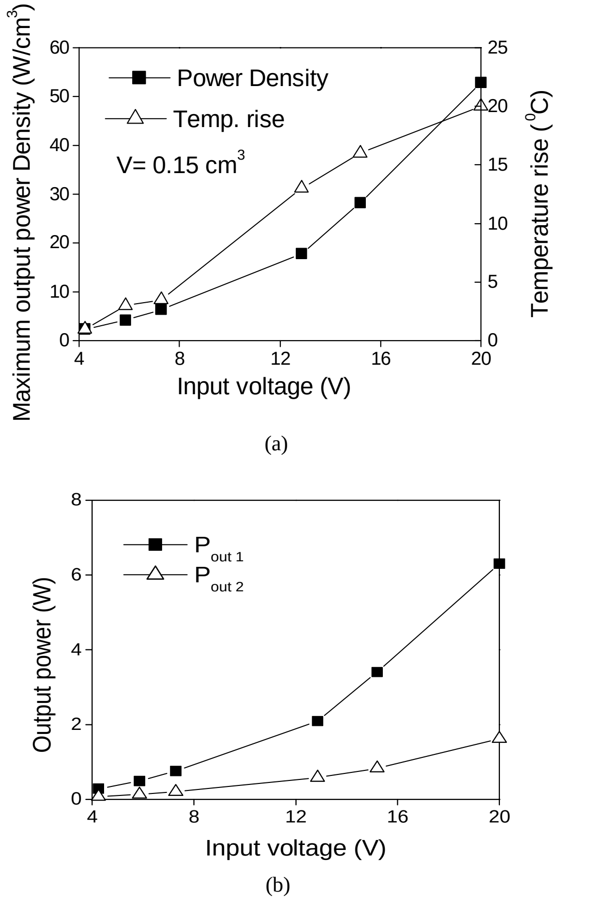

Fig. 6. (a) Relationship among the maximum output power density, temperature rise and input voltage of the proposed PT with matching loads. (b) Distributions of the output powers when the total output power reaches the maximum with respect to input voltage.

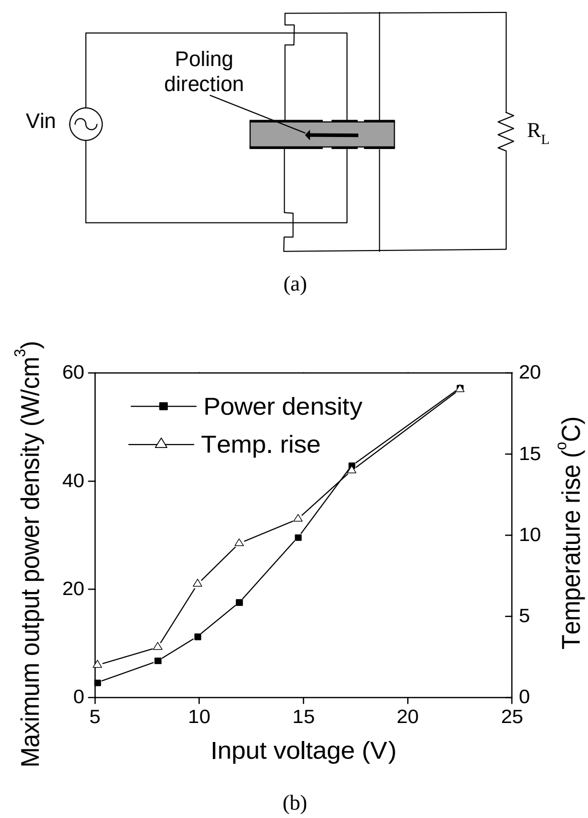

Fig. 7. (a) Constructions of the transformer with the two output parts in parallel. (b) Relationships among the maximum output power density, temperature rise and input voltage for the transformer with the two outputs in parallel.

driving frequency. In this experiment, the temperature rise of the transformer was below 5 °C.

Fig. 6(a) shows the relationship among the maximum output power density, temperature rise and input voltage of the PT with the matching loads. Here, the maximum output power density is with respect to the driving frequency for a given input voltage. It is seen that a maximum power density of 52.7 W/cm^3 can be obtained at a temperature rise lower than 20 °C. When the input voltage is over 20 $V_{rms,}$ the temperature rise of the transformer increases rapidly, and the characteristics of the transformer become quite unstable. When the temperature of the piezoelectric transformers is too high, the internal loss of the PZT material becomes very large. This increases the temperature of the transformers further and makes the operation unstable. Fig. 6(b) shows the distributions of the output powers when the output power density reaches the maximum in Fig. 6(a). It is seen that, the ratio of $P_{out\,1}$ and $P_{out\,2}$ is approximately constant (≈3.8) when the input voltage is less than 10 V_{rms}, and this ratio increases with the increase of the input voltage when the input voltage is larger than 10 V_{rms}. This is because the equivalent circuit parameters change with the vibration velocity of the PT, and the change of these parameters results in the change of the voltage gain.

In order to broaden the applications of the piezoelectric transformer with dual outputs, a parallel combination of the two outputs of transformer was experimentally investigated. Fig. 7(a) shows the constructions of the transformer with the two output parts in parallel. The matching load resistance R_L is 140 Ω. Fig. 7(b) shows the relationships among the maximum output power density, temperature rise and input voltage for the transformer with the two outputs in parallel. It is seen that the maximum output power density of this operation (57.3 W/cm^3) is higher than that of the dual-output transformer (52.7 W/cm^3) under the matching load conditions. On the impedance curve of the input part of the transformer with dual outputs, there are two anti-resonance peaks because the two outputs of the transformer are different. This results in a lower k_{eff}. However, the transformer with two outputs in parallel has one anti-resonance peak. This results in a relatively higher k_{eff}. So the maximum output power density of the transformer with the two outputs in parallel is higher than that of the transformer with dual outputs.

5. Summary

A high power-density dual-output piezoelectric transformer was proposed and experimentally investigated. With a novel lead wires connection, at a temperature rise lower than 20 °C, the piezoelectric transformer has a maximum output power density of 52.7 W/cm^3 with an efficiency of 88%. The maximum efficiency of this piezoelectric transformer is 95%. By using a parallel combination of the two outputs of the proposed transformer, a higher output power density of 57.3 W/cm^3 can be achieved at the temperature rise lower than 20 °C.

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