Lead-free multilayer piezoelectric transformer

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In this article, a multilayer piezoelectric transformer based on lead-free Mn-doped $0.94(Bi_{1/2}Na_{1/2})TiO_3-0.06BaTiO_3$ ceramics is presented. This piezoelectric transformer, with a multilayered construction in the thickness direction, is 8.3 mm long, 8.3 mm wide, and 2.3 mm thick. It operates in the second thickness extensional vibration mode. For a temperature rise of 20 °C, the transformer has an output power of >0.3 W. With a matching load resistance of 10 Ω, its maximum efficiency approaches 81.5%, and the maximum voltage gain is 0.14. It has potential to be used in low voltage power supply units such as low power adapter and other electronic circuits. © *2007 American Institute of Physics.* [DOI: 10.1063/1.2432245]

When piezoelectric transformers were developed in the 1950s,[1] they were not commercially pursued to a large extent due to poor material reliability and competition from electromagnetic transformers. Owing to the rapid development of portable electronic devices such as notebook computers and digital video cameras, there are great demands in miniaturized and highly efficient transformers. Losses due to the skin effect, thin wire, and core loss in electromagnetic transformers increase significantly as the size of the transformer is reduced. On the contrary, compared with electromagnetic transformers, piezoelectric transformers have a larger power to volume ratio, higher efficiency, and are free of electromagnetic noise and nonflammable. In general, piezoelectric transformers can be classified into two types. One type has a voltage gain (=ratio of output and input voltages) of >1 (step-up transformers) and a high output voltage of more than several hundred volts.[1–3] The other type of transformers has a voltage gain of <1 (step-down transformers) and a low output voltage of several volts.[4–7] The former can be used in cold cathode fluorescent lamp inverters for liquid crystal displays, and the latter can be used in the adapters for power supply units. In this article, the multilayer piezoelectric transformer presented is a step-down transformer.

The most widely used piezoelectric ceramics are lead-based ceramics, especially $Pb(Zr,Ti)O_3$ (PZT), because of their excellent piezoelectric properties. With concern in the environmental pollution of PbO evaporation, lead-free piezoelectric ceramics have recently attracted considerable interest to replace the lead-based material systems. A $(Bi_{1/2}Na_{1/2})TiO_3-BaTiO_3$ system (BNT-BT) has been found to be a promising lead-free piezoelectric composition. This BNT-BT system has a rhombohedral (F_R)-tetragonal (F_T) morphotropic phase boundary (MPB).[8] For compositions near the MPB, a high electromechanical coupling factor k_t along with high mechanical strength can be obtained. Since BNT-BT ceramics is a material with a large piezoelectric

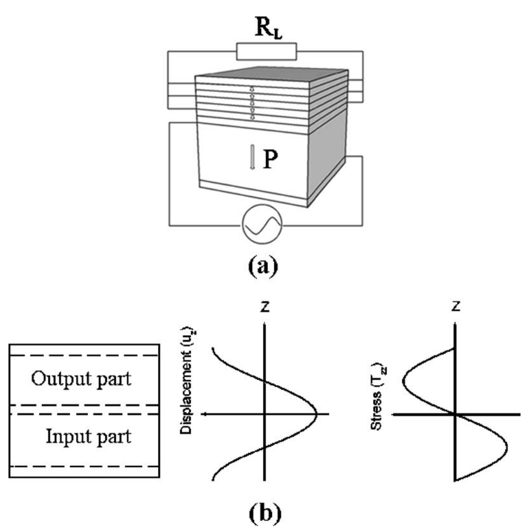

FIG. 1. Multilayer piezoelectric transformer operating in the second thickness extensional vibration mode: (a) construction and (b) distribution of displacement and stress.

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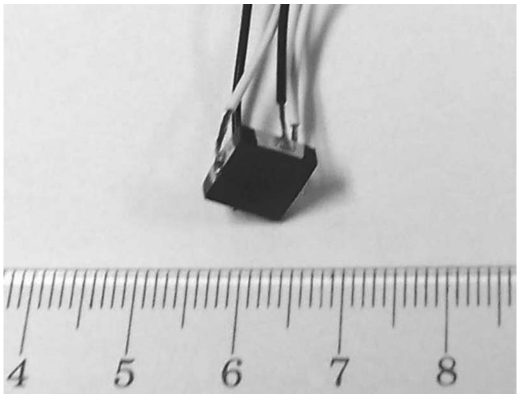

FIG. 2. Photograph of the multilayer piezoelectric transformer.

anisotropy between k_t and k_p, it has potential to be used for high frequency multilayer piezoelectric transformer operating in the thickness extensional vibration mode.[4]

The configuration of the multilayer piezoelectric transformer is shown in Fig. 1(a). It is fabricated using the lead-free Mn-doped $0.94(Bi_{1/2}Na_{1/2})TiO_3-0.06BaTiO_3$ (abbreviated as BNT-BT6) ceramics. The input part consists of one piezoelectric ceramic layer while the output part consists of five stacked thin piezoelectric ceramic layers. All the ceramic layers are polarized in the thickness direction, where these polarized directions are alternately opposing in the output part. An insulation layer is set between the input and output parts to isolate them from each other. In addition, two inactive layers are added on the top and bottom surfaces of the transformer, respectively.

This type of multilayer transformer operates in the second thickness extensional vibration mode,[4] and the vibration displacement and stress as a function of position along the thickness direction are schematically shown in Fig. 1(b). When an ac voltage is applied to the input electric terminals of the piezoelectric transformer at the frequency of the second thickness mode resonance, the thickness extensional vibration is excited through the converse piezoelectric effect and the relevant electromechanical coupling factor is k_t. The mechanical vibration is propagated to the output part, and the voltage would be generated at the output electric terminals by the direct piezoelectric effect. In this case, the output voltage depends on the thickness ratio of the individual layers in the input and output parts.

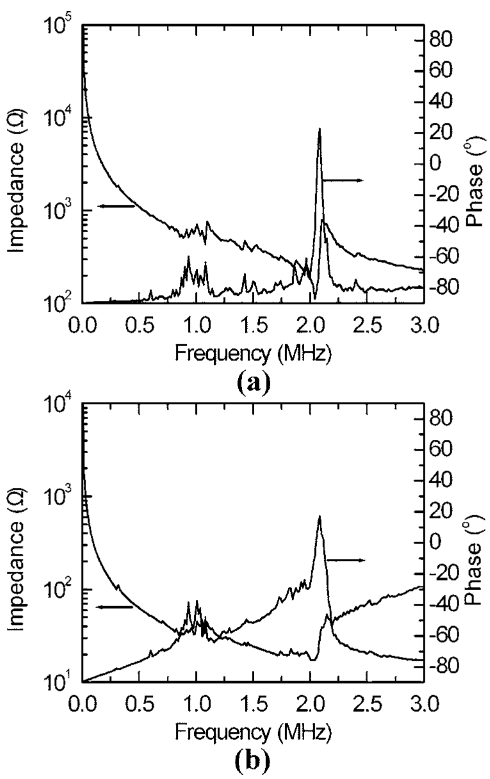

FIG. 3. The impedance/phase spectra of the (a) input part and (b) output part of the piezoelectric transformer.

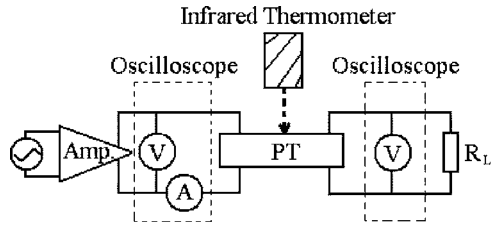

FIG. 4. Experimental setup for measuring the characteristics of the piezoelectric transformer.

The BNT-BT6 powders were fabricated by the solid state reaction. Slurry based on BNT-BT6 material was prepared for roll casting, and then it was cast into green sheets with the thickness of about 230 μm. These green sheets were subsequently cut into 10×10 mm^2 squares. Internal cofiring electrode (Ag/Pd=80/20) with a rectangular shape (6×8 mm^2) was painted onto the green sheets using a screen-printing process. A compact multilayer stack of 13 layers as shown in Fig. 1(a) was made of the ceramic green sheets by hot pressing. The multilayer stack was sintered at 1060 °C for 2 h in an air atmosphere. Fired-on silver paste was used as outer electrodes. The sample was poled under dc electric field of 3.5 kV/mm for 15 min in silicone oil at 80 °C. Figure 2 shows a photograph of the multilayer piezoelectric transformer with 8.3 mm length, 8.3 mm width, and 2.3 mm thickness. Piezoelectric properties of BNT-BT6 ceramics were measured by means of the resonator method on the basis of IEEE standard using an impedance analyzer (Agilent 4294A).[9] The piezoelectric coefficient d_{33} was measured by a d_{33} meter (ZJ-3B) which was supplied by the Beijing Institute of Acoustics, Academia Sinica. The measured properties of the BNT-BT6 ceramics are shown in Table I.

Figure 3 shows the measured input impedance and output impedance spectra as a function of frequency of the BNT-BT6 multilayer piezoelectric transformer. Output terminals were short circuited when the input impedance was measured. Similarly, when the output impedance was measured, input terminals were short circuited. From Fig. 3, it is seen that the first thickness extensional vibration mode at

TABLE I. Properties of the BNT-BT6 ceramics

ρ (kg/m^3)	5780
Q_m	800
d_{33}(pC/N)	100
k_t	0.46
k_p	0.10
$\varepsilon_{33}{}^T/\varepsilon_0$ at 1 kHz	630

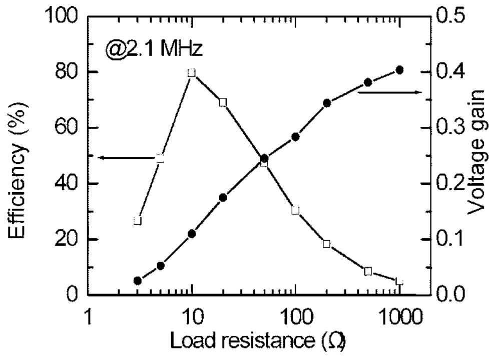

FIG. 5. Load resistance dependence of voltage gain and efficiency of the piezoelectric transformer at 2.1 MHz.

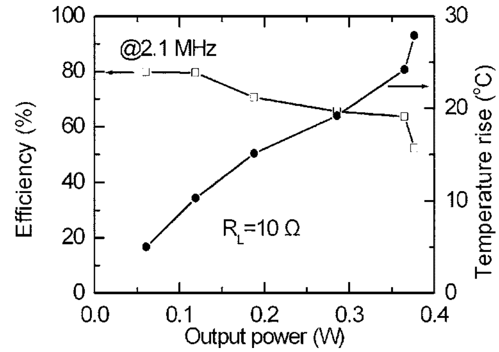

FIG. 7. Measured temperature rise and efficiency of the piezoelectric transformer with different output power, where load resistance is 10 Ω and driving frequency is 2.1 MHz.

about 1 MHz is affected by transversal vibration modes. At around 2 MHz, a strong resonance can be seen, which corresponds to the second thickness extensional vibration mode.

The characteristics of the piezoelectric transformer were measured using the experimental setup as shown in Fig. 4. The transformer was driven by an ac signal generated by a function generator and amplified by a high speed power amplifier. A pure resistive load R_L was used. The voltage, current, and power of the input and output parts were measured by using two oscilloscopes. The temperature change of the transformer was measured by an infrared thermometer about 1 min after applying the input voltage. The temperature rise can be controlled by properly tuning the input voltage.

In order to find out the matching load, where the efficiency of a piezoelectric transformer attains a maximum value, different load resistors were used. Figure 5 shows the effect of the load resistance on the voltage gain and efficiency of the transformer. The frequency was 2.1 MHz. It is found that the voltage gain of the transformer gradually increases with the load resistance. For the efficiency, a maximum efficiency of 79.5% was obtained when the load resistance was 10 Ω. Thus, the matching load of the BNT-BT6 multilayer piezoelectric transformer is about 10 Ω. According to the theoretical analysis, the matching load is equal to $1/(\omega C_{d2})$, where C_{d2} is the damped capacitance of output part.[10] The experimental result is close to the calculated value of 15 Ω.

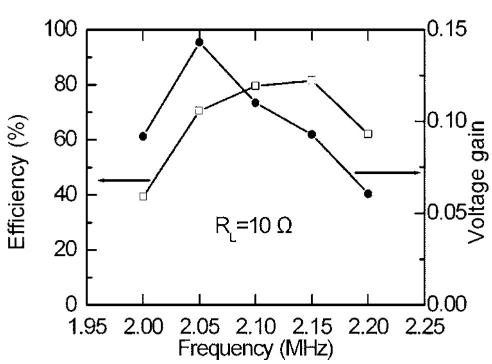

FIG. 6. Frequency dependence of voltage gain and efficiency of the piezoelectric transformer with the load resistance of 10 Ω.

The frequency dependences of the voltage gain and efficiency of the piezoelectric transformer with the load resistance of 10 Ω are shown in Fig. 6. During the measurement, the temperature rise was less than 10 °C. A maximum voltage gain of 0.14 and a maximum efficiency of 81.5% were obtained at 2.05 and 2.15 MHz, respectively. As mentioned above, the maximum voltage gain can be changed by adjusting the number of ceramic layers in the output part. It is believed that the maximum efficiency can be improved by increasing Q_m and k_t/k_p of the ceramics and reducing the portion of the inactive parts in the transformer.

The relationship among efficiency, temperature rise, and output power of the transformer connected with the load resistance of 10 Ω at 2.1 MHz is shown in Fig. 7. It is seen that a maximum output power of 0.3 W can be obtained. The efficiency of the transformer approaches 65% with a temperature rise of 20 °C. The maximum output power with higher efficiency can be further increased by fine tuning the driving frequency.

A lead-free BNT-BT6 multilayer piezoelectric transformer operating in the second thickness extensional vibration mode has been fabricated and characterized. The experimental results show that it has an output power of >0.3 W with a temperature rise of 20 °C. With a matching load resistance of 10 Ω, its maximum efficiency is 81.5%, and the maximum voltage gain is 0.14. It has potential to be used in low voltage power supply units such as low power adapter and other electronic circuits.

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