MICROFABRICATED BULK PZT PIEZOELECTRIC DISK TRANSFORMERS

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ABSTRACT

A new class of miniature monolithic piezoelectric transformer that leverages a simple two-mask bulk piezoelectric microfabrication process is presented. A millimeter-scale transformer design based on a disk-shaped resonator topology with annular electrodes is fabricated to produce step-up voltages in a compact form factor. The radial vibration characteristics and voltage gain of the bulk transformers under varying impedance loads have been analyzed experimentally, and compared against an electromechanical model of transformer performance. A maximum voltage gain of 7.3 was obtained.

INTRODUCTION

Piezoelectric transformers are resonant electromechanical devices which enable efficient AC voltage conversion. Compared to conventional electromagnetic transformers, piezoelectric transformers offer many advantages including low weight, high efficiency, and high input and output impedances to minimize loading effects. In addition, favorable scaling of piezoelectric transduction allows device dimensions to be significantly reduced while retaining acceptable performance[1].

Piezoelectric transformers have been widely studied[2,3,4]. At the macro scale, multilayer Rosen type bar transformers are commonly used in many applications, such as cold cathode fluorescent lamps, inverters for liquid crystal displays, and AC-DC converters for power supplies [1,2,5]. However, the fabrication of multilayer Rosen transformers is not well suited to miniaturization, prohibiting their use in a range of small scale systems such as interfaces for micro power harvesting platforms that demand efficient and high gain voltage conversion. An alternate transformer topology based on a disk-shaped resonator with annular electrodes can avoid this limitation, but fabrication by traditional machining or solution casting methods have limited the size of these devices to the range of several centimeters or more[6,7,8].

In this paper, disk-type step-up transformers with diameters ranging from 1-10 mm are studied. The step-up transformers are fabricated by a micro powder blasting technique that provides photolithographic control over transformer geometry, using high quality bulk lead zirconate titanate (PZT) as the piezoelectric substrate material. While microfabricated thin film piezoelectric

transformers employing high-Q silicon substrates have been reported, a significant advantage of the bulk PZT transformers described in this work is their high power handling capabilities. While heat removal presents an upper limit to power handling in macro scale piezoelectric transformers, the small Biot numbers associated with the millimeter scale devices reported here ensure that power handling is limited by energy density rather than thermal performance. As a result, power handling scales linearly with piezoelectric layer thickness, enabling the microfabricated bulk transformers to support power levels of 3.4-9.2 W/cm³.

A micrograph of a fabricated 1 mm diameter PZT transformer is shown in Figure 1. The transformer is operated in its fundamental radial vibration mode. An electric field (E) is applied across the thickness of the bulk PZT through an input electrode. A radial strain is thereby generated within the PZT through the transverse d_{31} coupling coefficient, and converted to a voltage at the output electrode [9]. Using the developed microfabrication methods[9], millimeter-scale piezoelectric transformers were successfully fabricated and characterized. The radial vibration characteristics and voltage gain of the bulk transformers under varying impedance loads were analyzed experimentally, and compared against an electro-mechanical model of transformer performance.

THEORETICAL BACKGROUND

Figure 2 shows the schematic diagram of a disk-type transformer, with R represents total radius and h defines the thickness of the transformer. The planar vibration analysis of a thin ($h \ll R$) circular disk is[10,11,12]:

$$\frac{d^2 U}{dr^2} + \frac{1}{r} \frac{dU}{dr} - \frac{U}{r^2} - \rho \omega^2 S_{11}^E (1 - \nu_p^2) U = 0 \quad (1)$$

$$U(r) = C J_1(\beta r) \quad (2)$$

$$\beta^2 = \rho \omega^2 S_{11}^E (1 - \nu_p^2) \quad (3)$$

$$f = \frac{\beta}{2\pi \sqrt{\rho S_{11}^E (1 - \nu_p^2)}} \quad (4)$$

where $U, \rho, S_{11}^E, \nu_p, \beta$ represent the displacement of the vibration, density, elastic compliance coefficient, Poisson's ratio, and Bessel function coefficient of the piezoelectric transformer respectively.

The equivalent circuit of the piezoelectric transformer is shown in Fig. 3. Turn ratio, effective mass, stiffness and damping factor can be calculated as follow:

$$F(s) = (j\omega)U(s)(L_m S + R_m + \frac{1}{C_m S}) \quad (5)$$

$$L_m = m_{eff} = \frac{2\pi \rho \int_0^R r J_1^2(\beta r) dr}{J_1^2(\beta R)} \quad (6)$$

$$C_m = \frac{1}{\omega_0^2 \cdot L_m} \quad (7)$$

$$R_m = \frac{\omega_0^2 \cdot L_m}{Q} \quad (8)$$

$$n_1 = \frac{2\pi (R J_1(\beta R) - R_i J_1(\beta R_i)) d_{31}}{S_{11}^E (1 - \sigma) J_1(\beta R)} \quad (9)$$

$$n_2 = \frac{I_{out}}{U'(BR)} = \frac{2\pi (R_0 J_1(\beta R_0) d_{31}}{S_{11}^E (1 - \sigma) J_1(\beta R)} \quad (10)$$

Figure1: Fabricated 500 μ m radius bulk PZT transformer.

Figure 2: Schematic diagram of a transformer showing electrode geometry.

Figure 3: Equivalent circuit of a piezoelectric transformer.

Based on the equivalent circuit, the theoretical model and PZT characteristics the optimum designs for the maximum gains for different range of PT have been obtained.

Experimental Studies

Aluminum (Al) wet etch for electrode patterning and micropowder blasting for selective PZT etching were combined in a two-photomask process to fabricate bulk piezoelectric transformers from a 7.24 cm square and 127 μm -thick type-5A PZT sheet (PSI5A4E sheets, Piezo Systems, Inc.). In order to provide a robust substrate the PZT was temporarily bonded to a 10 cm diameter silicon wafer using a sacrificial layer of an adhesive wax (Crystalbond 509). Bonding was performed by mounting the PZT sheet manually on melted wax at 130 $^{\circ}\text{C}$. The PZT has nickel metal layer on both sides. The nickel was removed using a 5 min wet etch in a nickel etchant. The transformer's input and output electrodes were patterned by 500 nm Al deposition by electron beam evaporation followed by spin coating a 1.5 μm thick layer of positive imaging resist. UV exposed resist was developed using CD-30 developer for 1 min and Al was wet etched in Aluminum etchant for 5 min at 55 $^{\circ}\text{C}$ to create the electrode patterns on the PZT surface. Micropowder blasting of the PZT was performed by laminating a 50 μm thick dry film photoresist as an etch mask for micropowder blasting of the PZT in a commercial laminator followed by UV exposure.

A benchtop microabrasive blasting workstation was applied for micropowder blasting using 25 μm alumina particles. The abrasive nozzle pressure was 55.16 N/cm^2 and its distance from the PZT substrate was 7 cm.

RESULTS AND DISCUSSION

Using the developed microfabrication methods, PZT transformers were fabricated and characterized. The radial vibration and voltage gain of the bulk transformers under varying impedance loads was analyzed experimentally, and compared against an electro-mechanical model of transformer performance. AC voltage generated by a function generator was applied to the transformer and the output voltage of the input and output electrodes were measured by an oscilloscope. An LM6172IN operational amplifier and a 100 $\text{k}\Omega$ resistor were used to make a unity gain buffer to eliminate the loading effect of the function generator in the input and the oscilloscope at the output of the transformer. Based on the manufacturer's data, the PZT sheet exhibits a typical mechanical quality factor of 80. An experimental quality factor of approximately 40 was measured in our tests,

presumably due to air damping since all measurements were conducted at atmospheric pressure. Theoretical gains, calculated using the measured quality factor of 40, are presented in Table 1 together with the resonance frequency for three selected resonator designs.

Table 1. Resonance frequency and maximum gain for three general dimensions

Device radius (mm)	R_o range (mm)	G (mm)	Resonant freq. (kHz)	Max. gain (Theory)	Max. gain (Experiment)
2.5	0.2-0.6	0.5	440	5.78	5.08
3.5	0.4-1	0.5	320	6.5	6.34
5	0.75-2.5	0.5	220	7.43	7.3

Figure 4: Experimental and theoretical gain versus R_o/R for devices of outer radius $R=5$ mm, 3.5 mm and 2.5 mm. The optimal ratio of 0.2 predicted by the analytical model is denoted by a dashed line. There is good overall agreement between the experimental and analytical data.

The correlation between theoretical and experimental device gain and output electrode radius ratio is shown in Figure 4. In the symmetric vibration of the PZT disk the radial displacement and radial stress are function of position along the radial direction of the disk. In order to operate in the third radial vibration mode, the transformer should be designed such that the annular gap is located at the position where the stress is minimum. For all devices, a maximum gain was found to occur when the output diameter was approximately 20% of the total diameter, in agreement with the analytical model predictions.

Figure 5. Voltage gain vs. load resistance for different resonance frequency

Figure 5 illustrates the voltage gain of bulk transformers under varying impedance loads. Voltage gain increases rapidly with increasing load resistance and saturates at higher load

resistance. This can be explained by the equivalent circuit of piezoelectric transformers. The load resistance R_L can affect the gain when is not much larger than the output capacitor $1/(\omega_o C_o)$ and the output voltage increases with the load resistance. The load can be considered as open when R_L is much larger than the output capacitor.

Figure 6. Efficiency vs. quality factor in theory. Efficiency of the transformer at the quality factor of 80 is equal to 40.

The maximum efficiency of a piezoelectric transformer can be obtained when the load resistance equals matching load, $1/(\omega_o C_o)$. The quality factor of the bulk PZT under vacuum is 80. According to the theoretical model the efficiency at this quality factor should be 40%. The vibration of the transformers has been measured in the air where the measured quality factor was 40. The experimental efficiency at this quality factor was 27% which showed a good agreement with the theoretical model. Since this transformer has high voltage gain and average efficiency, it is suitable for high voltage applications. The theoretical efficiency for different PZT quality factors are shown in Figure 6. The maximum gain measured at the maximum efficiency was 4.

Maximum output voltage of 58 V with respect to 20 V input voltage was measured for a 7 mm diameter device when different load resistances were used. The power density at the matching load of 5 k Ω was measured to be 9.2 W/cm³. However the transformer behaved stable, when the input voltage was greater than 10 V the temperature increased in the input opamp and limited the applied input voltage. The output gain for input voltage <10 at the matching load was 4 and it decreased to 2.9 for input values >10. Power densities of 7.1 W/cm³ and 3.4 W/cm³ were also measured for output load resistances of 1 k Ω and 100 Ω , respectively.

Figure 7 illustrates the linear relationship between gain and transformer radius. Gains of 3-7 were readily achieved by varying the radius from 1.5 mm to 5.5 mm while the gap was held constant at 500 μ m. As shown in equations 5-10, the turn ratios and the vibrational behavior of the transformers are a function of the total radius and their value increases with the greater device radius.

Figure 7. Gain vs transformer radius

CONCLUSION

The characteristics of a disk-shaped piezoelectric transformer have been studied theoretically and experimentally. A maximum gain of 7.3 at ideal load and maximum gain of 4 at the maximum efficiency were obtained, the highest reported gains for piezoelectric transformers of this size. For examples, these results compare favorably to the smallest disk transformer previously reported, which provided a maximum gain of 1.9 for a 1.3 cm diameter device [6].

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