Design Consideration for Nonlead Piezoelectric Transformers

Shashank Priya*, Hyeoungwoo Kim and Kenji Uchino

International Center for Actuators and Transducers

Pennsylvania State University, University Park, PA 16802.

Abstract

The aim of this paper is to find a suitable transformer design for nonlead materials. Lead-based piezoelectric materials have high density, electromechanical coefficients and dielectric constants as compared to that of nonlead materials. Hence, if similar design such as Rosen-type is employed for designing the transformer with nonlead material then gain and output power of the transformer will be significantly inferior and below the specifications of the present day applications. Various transformer structures are described in this study. The choice of the structure depends on the material constants.

Introduction

The piezoelectric transformer offers several advantages compared to the electromagnetic ones:

1. Higher electromechanical power density
2. No electromechanical noise
3. Higher efficiency at resonance
4. Miniaturization is possible
5. Wide frequency range
6. Nonflammable and
7. Simpler fabrication technique

Due to these factors piezoelectric transformer (PT) market has grown significantly in the past decade. Technological advancements in many arenas have opened door for the PT. In addition to the conventional applications such as backlight inverters, power supplies for notebook computers, AC-DC converters, power supplies for displays, car navigation system, LCDs for small screen devices, cathode ray tubes, image intensifiers, air cleaners and copying machines, various new areas have been proposed for PT's. These include ozone filters, negative ion generator, igniter for gas discharge element, galvanic isolation element in IC's, high voltage generators, robotics and toys, power sensing, automobile lighting and general-purpose lighting. Various transformer designs have been proposed to meet the variety of specifications in both step up and step-down applications. In step-up applications Rosen type [1] still remains the preferred design for the manufacturers. Other structures such as alternately poled transformers and radial mode transformers are not yet commercialized. In step-down applications, 2^{nd} harmonic thickness mode transformer [2] and radial mode transformer [3] are the preferred designs.

Currently, ceramic transformer industry is facing a critical challenge. This confront comes from the regulation imposed upon the usage of lead materials. As of now there is no

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nonlead high power piezoelectric material, which can be used for the transformer application. In order to overcome this hurdle a two-way program is important:

1. Develop a high power nonlead material
2. and Design new transformer structures offering considerable latitude on the selection of vibration modes.

This paper focuses on the 2nd program. Since lead-based high power piezoelectrics ($Pb(Zr_xTi_{1-x})O_3$ (PZT) based solid solutions, such as PZT-$Pb(Mn_{1/3}Sb_{2/3})O_3$ [4], PZT-$Pb(Ni_{1/3}Nb_{2/3})O_3$ [5], PZT-$Pb(Mn_{1/2}W_{1/2})O_3$ [5], PZT-$Pb(Ni_{1/2}W_{1/2})O_3$-$Pb(Mn_{1/3}Nb_{2/3})O_3$ [6], PZT-$Pb(Sb_{1/2}Nb_{1/2})O_3$-$Pb(Zn_{1/3}Nb_{2/3})O_3$ [7] etc.) offer high piezoelectric constants and electromechanical coupling factors in all vibration modes, it is easier to design the transformer structure with these materials. Nonlead materials have extremely low piezoelectric and electromechanical constants as compared to lead materials. Table 1 compared the properties of the PZT and the prominent non-lead based systems. The data shown in this table has been collected from various publications [5]. It can be easily deduced from the data shown in this table that none of the nonlead ceramics qualifies for the transformer application. It is for this reason that the 2nd program mentioned above is very important. Various transformer structures are proposed and discussed in this study, which can be adopted depending upon the material properties. For example – in the case of (Na, K)NbO_3 ceramics [8], the material has good longitudinal mode and radial mode coupling factors. Hence, a design that utilizes these two modes for voltage transformation would be the ideal one for these ceramics. Another interesting possibility is of using the unipoled transformers for the nonlead ceramics.

Table 1: Properties of lead-free piezoelectric ceramics.

	Symbol	$\varepsilon_{33}^T/\varepsilon_0$	Qm	d_{33} (pC/N)	d_{31} (pC/N)	k_{33} (%)	k_p (%)	Tc (°C)
PZT (Mn, Fe doped)	**PZT**	1500	1000-2000	300	-100	60	50	300
(Bi,Na)TiO_3	**BNT(1)**	600	500	120	-40	45	25	260
Bi-layer	**SBT(1)**	150	>2000	20	-3	20	3	550
	NCBT(1)	150	–	15	-2	15	2	>500
	NCBT(1)(HF(2), TGG(2))	150	–	40	-2	40	2	>500
(Na,K)NbO_3	**KNN(1)**	400	500	120	-40	40	30	350
Tungsten Bronze	**SBN(1)**	500	–	120	–	30	–	250
Others	**BT(1)**	1100	700	130	-40	45	20	100

(1) BNT: $(Bi_{1/2}\,Na_{1/2})TiO_3$, **SBT**: $SrBi_4Ti_4O_{15}$, **NCBT**: $(Na_{1/2}Bi_{1/2})_{0.95}Ca_{0.05}Bi_4Ti_4O_{15}$, **KNN**: $(K_{1/2}Na_{1/2})NbO_3$, **SBN**: $(Sr,Ba)Nb_2O_6$, **BT**: $BaTiO_3$

(2) HF: Hot Forging method, **TGG**: Templated grain grouth method

Transformer designs:

a). Radial-Transversal mode transformer (RTM)

Figure 1 shows the design of this transformer. The ceramic constitutes of a ceramic disk with two bars. This transformer can be made by conventional ceramic manufacturing method if a die of similar shape is used or by lamination technique where two bars are bonded with the disk at the central point. In the case of lamination technique, the ceramic material for the bar and disk can be different. Textured ceramics with anisotropic properties can be easily utilized in this design.

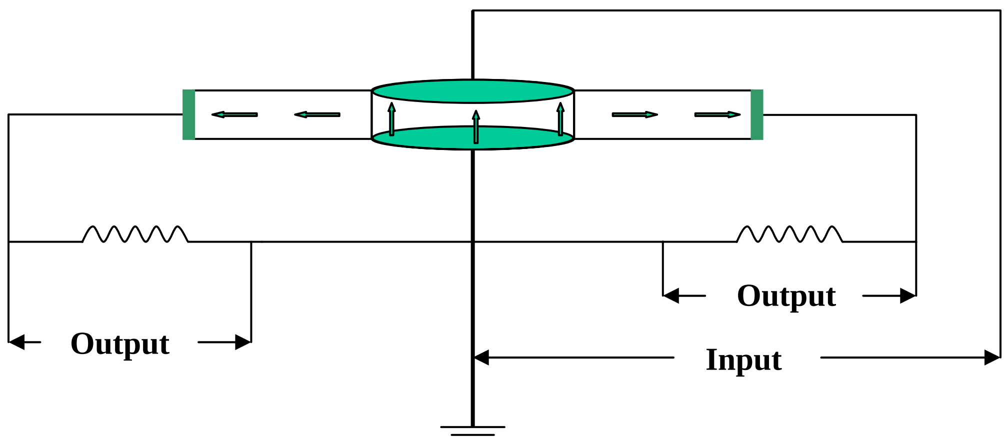

Figure1. Schematic diagram of the Radial-Transversal mode transformer. Two outputs are shown here separately for the convenience. The green color shows the electroded region and the arrows shows the poling direction.

The diameter of the ceramic disk is such that the resonance frequency (f_r) of the bar is similar to that of the disk, according to the condition:

$$\frac{\psi_1}{\pi D}\cdot\frac{1}{\sqrt{s_{11}^E\rho(1-\sigma^2)}}=\frac{1}{2L}\cdot\sqrt{\frac{1}{s_{33}^D\rho}} \quad (1)$$

where ψ is the Bessel function, D is the diameter of the disk, ρ is the density, σ is the Poisson's ratio, s is the elastic compliance and L is the length of the bar. Since for most of the ceramics, ψ_1 = 2.05 and σ = 0.3, substituting these numbers in the Eq. 1 and simplifying for length to diameter ratio results in Eq. 2:

$$\text{or} \qquad L/D \sim 0.731\sqrt{s_{11}^E/s_{33}^D} = 0.731\sqrt{\frac{s_{11}^E}{s_{33}^E(1-k_{33}{}^2)}} \quad (2)$$

Eq. 2 can be solved for a specific material and required L and D can be obtained. For e.g., the material constants for APC841 are s_{11}^E = 11.7 x 10^{-12} m^2/N, s_{33}^E = 17.3 x 10^{-12} m^2/N and k_{33} = 0.68, so L/D ~ 1.26. In Fig. 1 two outputs are shown for the transformer. These can be connected together through a common load resistance to provide higher power. This design has higher power per unit volume as compared to that of the Rosen-type, since the gain (g) is proportional to $2k_pk_{33}Q_m$ as compared to $k_{31}k_{33}Q_m$. Another advantage of this transformer is that input and output are isolated from each other. The input and output ceramic components can be easily multilayered to provide the required equivalent circuit parameters for matching the specific requirements.

(b) Longitudinal-Transversal mode transformer (LTM)

Figure 2(a) shows the design of LTM transformer. In this transformer, there are 3 layers. Top and bottom layers are input and are poled in the thickness direction, while middle layer is output and is poled in the length direction. Each layer is isolated from each other by glass. This figure also shows the electrode connection for this transformer.

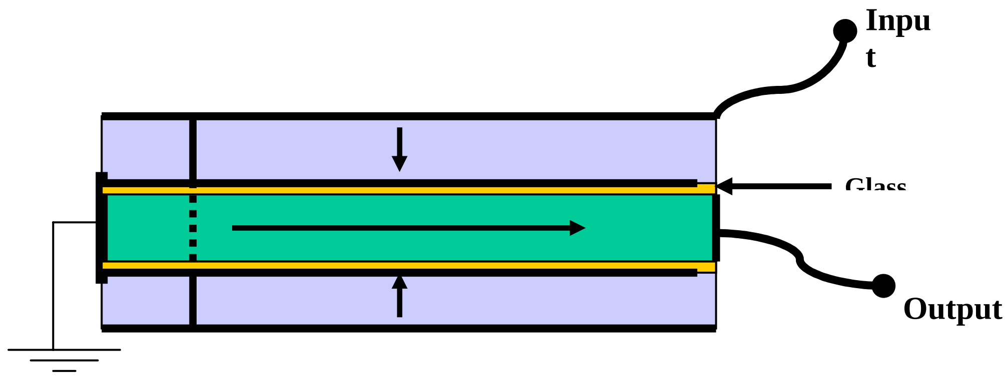

Figure 2(a). Schematic diagram of the Longitudinal-Transversal mode transformer. Dark lines indicate the electrodes.

On application of the electric field, the input layers resonate in the transversal mode and this causes vibration in the longitudinal mode in the middle layer. Both input and output layers can be multilayered as shown for input in Figure 2(b). The main advantage of this transformer is that it can deliver high power with a moderate step-up ratio. The dimension of the transformer should be chosen as:

$$\text{Input/Output Length} = \left(1 - k_{33}^{\;2}\right)^{1/2} \quad (3)$$

$$\text{Output/Input Width} = \left(1 - k_{33}^{\;2}\right)^{1/2} \quad (4)$$

The thickness of the input layers can be chosen according to the gain requirements. Thin ceramics tend to deliver higher gain but thin plates tend to dissipate energy in the flexural mode. In order to avoid the flexural vibrations the ceramic plates can be curved slightly about the axis parallel to the length. The input should be held at the central node for operation in the fundamental mode.

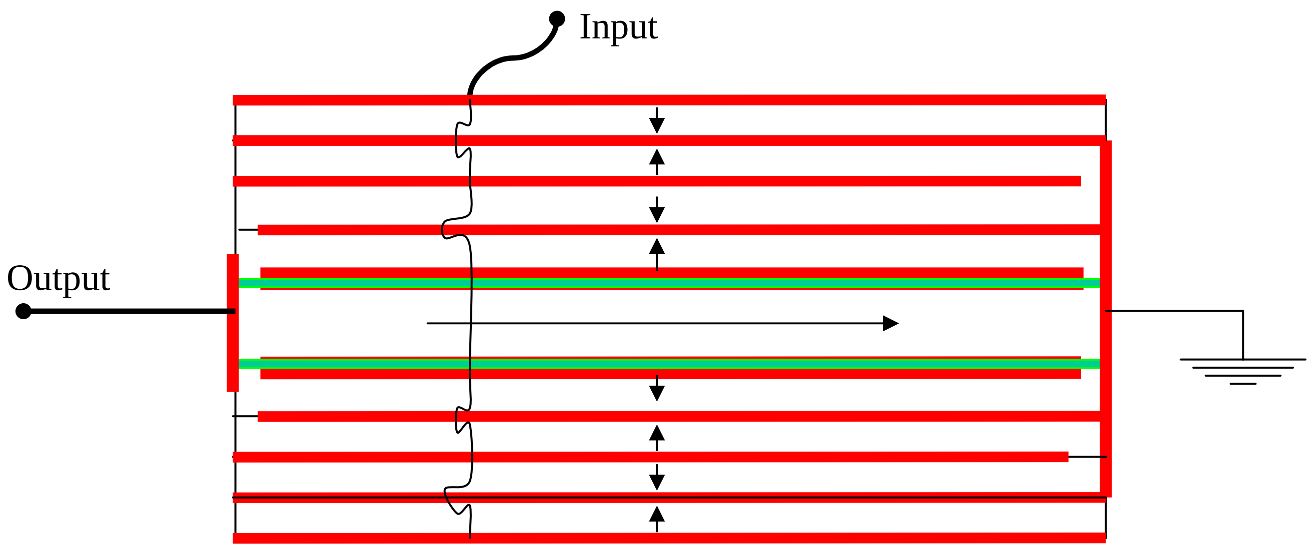

Figure 2(b). Schematic diagram of the multilayer Longitudinal-Transversal mode transformer. Dark lines indicate the electrode pattern.

(c) Ring type transformer (RTT)

Figure 3(a) shows the design of the ring type transformer. This structure offers considerable latitude in terms of the obtainable properties. It can work in both the step-up and step-down mode depending upon the connection. The tuning of the voltage gain and power requirements is straightforward and it makes this design particularly practical. In Fig. 3(a) the input and output are shown to occupy half of the total area of the ring. The input is poled along the thickness direction while the output is poled along the radial direction. In the input, the

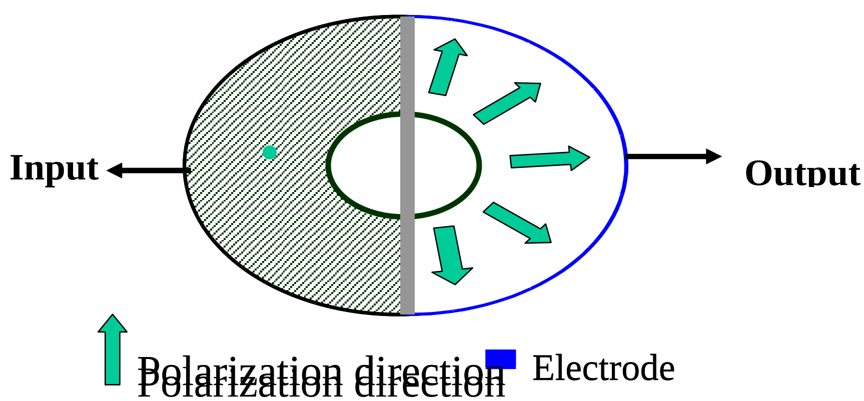

Figure 3(a). Schematic diagram of the Ring type transformer. Dark blue line indicates the electrode. The gray rectangle in the center region indicates the isolation which is the unelectroded region of the ceramic.

electrode is put on the top and bottom surface while in the output part the electrode is put on the inner and outer edges. In this poling condition, this is a step-up transformer. For a given outer and inner diameter of the ring, the input and output region should be optimized to obtain the highest efficiency. Figure 3(b) shows such an optimization done for a ring having an outer diameter of 27.5 mm and inner diameter of 6 mm.

In the step-down mode the connections are inverted, i.e., the radial poled becomes the input and the thickness poled part becomes the output. For large step-down, the output area should be as high as possible but larger step-down results in lower power. Hence, depending upon the dimension of the disk the tuning of the gain and power can be done.

One of the important issues with the ring type transformer is poling. A special poling condition is required in order to obtain a crack free sample. For a general PZT-based high power material, the poling should be performed in the following way:

Step 1: Initially, the fired-on silver electrode is screen-printed on the optimized input and output region.

Step 2: Next, the room temperature electrode is painted on top and bottom face of the ring such that the ring can be poled along the thickness direction.

Step 3: After drying the electrode the ring is poled along the thickness direction at a temperature of 80 – 120 ^{o}C by applying a DC field of 3 – 2.5 kV/mm.

Step 4: Remove the room temperature electrode and pole the ceramic in the output region along the transversal direction. There should be a gap (or isolation) of 1.5 – 2 mm between the input and region. The poling field along the transversal direction is between 1 – 1.5 kV/mm.

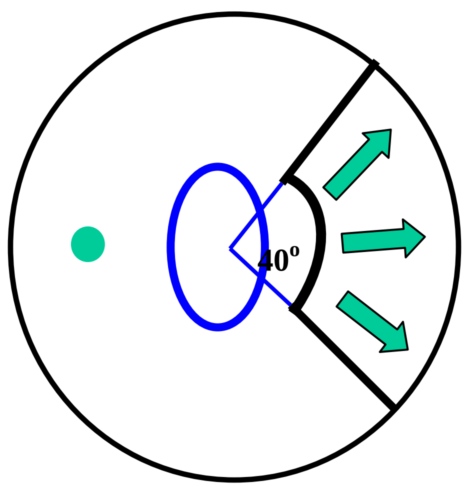

Figure 3(b). Schematic diagram of the optimized Ring type transformer for a ring having an outer diameter of 27.5 mm and inner diameter of 6 mm. Dark black lines indicates the electrode.

(d). Unipoled transformers

Unipoled transformers were firstly proposed by Berlincourt [9] and later studied in detail by Pitak et al. [10]. Figure 4 (a) and (b) shows the examples of unipoled structures which can be used for transformer applications.

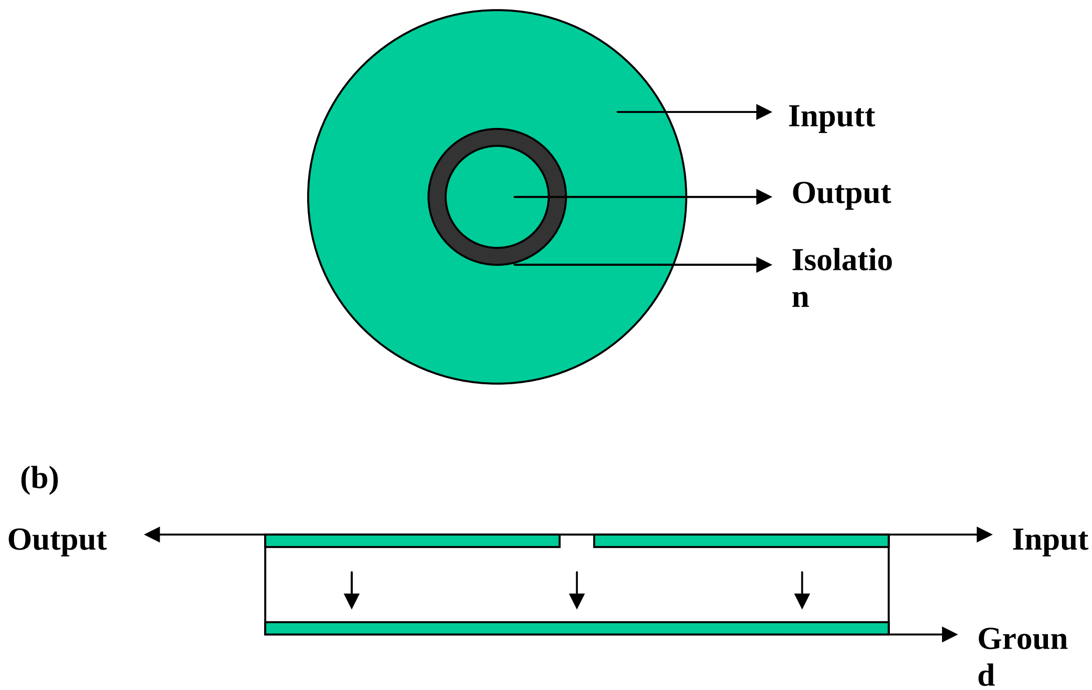

Figure 4: Design of unipoled transformers. (a) Disk type and (b) bar type. Poling is along thickness direction.

Results and Discussion

The transformer structures described in this study have been designed for incorporating with nonlead materials. Since all the material constants for a particular nonlead material is not available, a representative material of PZT-family (APC 841) was used for these calculations. Following table shows the results obtained:

Type	Size	Gain (V/V) (matching load)	Efficiency (%)	Mode
RTM	Disk Size: 15 x 1 mm^2 Bar Size: 9 x 3 x 1 mm^3	15	70	Step-up
LTM	27.45 x 6.0 x 2.3 mm^3	14	85	Step-up
RTT	Outer dia. – 29.1 mm Inner dia. – 8 mm Thickness – 1 mm Outer region angle = 40^o	30	65	Step-up
RTT	Outer dia. – 29.1 mm Inner dia. – 8 mm Thickness – 1 mm Outer region angle = 40^o	0.03	89	Step-down
Unipoled disk type	Total diameter – 29 mm Output region dia. – 11 mm Thickness – 1 mm	12	94	Step-up

The data shown in Table 2 was based on the structures designed by using FEM simulation by Attila software. It is worth pointing out that these are not the optimized designs for these sizes. The data clearly shows that all of these designs are very promising. They offer much higher degree of freedom in designing the transformer through a particular type of material. Out of the various structures considered in this investigation, unipoled transformers appear to be the best choice. The unipoled structures are easy to fabricate and much cheaper than other designs. The integration of these designs with nonlead materials is the next step and is now in progress.

Conclusion

This study describes new transformer designs. These designs are easy to fabricate such as shape of the ceramic, poling and assembly. The main advantage of these designs is that they exploit a particular vibration mode so depending upon the material constants a suitable design can be selected. All the transformer structures were simulated using the Attila software in order to confirm the working mode. Further, each type of transformer was fabricated and the gain and efficiency of the transformer were measured under the low power condition. These measurements show that unipoled transformers are the most promising structures.

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