Ultrasonic Piezoelectric Transformers for Power Conversion

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Introduction to MMech

- Company Name: Micromechatronics, Inc.
- Head Office: State College, PA 16803
- Founded: October 1st, 2004
- Roots: Spin off Int. Center for Actuators and Transducers at PSU
- web: www.mmech.com

Product Portfolio

<table>
<thead>
<tr>
<th>Design Software</th>
<th>Motion Control</th>
<th>Energy Conversion</th>
<th>Industrial Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATILA FEA Software, GiD Pre/Post Processor</td>
<td>Piezo Elements, Actuators, Stages, Ultrasonic Motors</td>
<td>Piezo Generators, Piezo Transformers</td>
<td>Ultrasonic Cleaning, Cutting, Measuring</td>
</tr>
</tbody>
</table>

April 22, 2013  UIA 42nd Annual Symposium
Piezoelectric Transformers: Background

**Piezoelectricity - Basics**

**Inverse Piezoelectric Effect**

**Direct Piezoelectric Effect**

Electrical to Mechanical energy conversion

Mechanical to Electrical energy conversion

A piezoelectric transformer is an energy conversion solid state device that uses an acoustic vibration to transfer/convert electrical-to-electrical energy at different voltage levels using piezoelectric materials. An standing wave at one of the resonant modes of the transformers excites the mechanical vibration.

The first ceramic Piezoelectric Transformer was developed by Charles A. Rosen and Keith Fish in 1954.
Piezoelectric Transformers: Background

**Historical Background - High Voltage conversion**

1927 First Studies. Alexander M. Nicolson proposed some basic PTs using Rochelle salt crystals.

1954 Rosen-PT. First Piezo "Ceramic" Transformer.

1960 New Designs. H. Jaffe, D. A. Berlincourt followed w/ new designs (ex. Unipoled radial and contour-mode PTs)

70-80s First Applications (TV, ignition, gate drivers, etc)

90s CCFL Backlighting

**Historical Background - “Step-down” Power PTs**

1992 US5329200 Thickness PT.

1997 US5969954 Longitud. PT.

1997 US5969954 Transver. PT.

1998 Contour Mode

1998 Thickn Mode

Radial Mode

Contour Mode

Contour Mode

Thickness Vibration Mode

Thickness Polarization

Res. Freq: ~ 50-250kHz

Thickness Polarization

Res. Freq: ~ 50-100kHz

Thickness Polarization

Res. Freq: ~ 400kHz

Radial Vibration Mode

Contour Vibration Mode

Contour Vibration Mode

Thickness Vibration Mode

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Piezoelectric Transformers: Background

Historical Background

PT MARKET EVOLUTION

- New materials composition (on-resonance)
- Tape casting, multilayer techniques
- Compact and reliable packaging
- Integrated ICs to allow reliable control
- Better design tools (FEA-modeling)
- Consumer applications triggered the commercial volume application of PTs

Technology Survey - State of the Art Technology

- Rosen-PT Transformers
- Transon- Radial PT - 1st radial mode
Piezoelectric Transformers: Background

Technology Survey - State of the Art Technology

- 97% Size Reduction
- 85% Size Reduction
- 60% Size Reduction

<table>
<thead>
<tr>
<th>Power Density</th>
<th>Year</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>2W/in³</td>
<td>1980</td>
<td>Linear</td>
</tr>
<tr>
<td>65W/in³</td>
<td>2000</td>
<td>Switch-mode</td>
</tr>
<tr>
<td>450W/in³</td>
<td>2002</td>
<td>Piezo</td>
</tr>
<tr>
<td>&gt;1kW/in³</td>
<td>2003</td>
<td>Piezo</td>
</tr>
</tbody>
</table>

Linear > Switch-mode > Piezo

Operation

Different Modes of Operation

Gain, G(f)
Gain Phase, φ(f)
Design Process

Obtain the inverter and load model

The design of a PT for a specific application involves the consideration of the input and output circuitry.

The transformer parameters and transformer ratio have to ensure that this voltage can be met at the lower input voltage (in this example Vin_min = 25 Vdc).

Example:

V_{out,DC} = 6 V;
I_{out} = 2.5 A (P_{out} = 15 W)
Vin = 25 - 40 Vdc

\[ R_{L,dc} = 2.4 \, \Omega \]

Assuming \( V_f = 0.5 \text{V} \) and \( R_f = 0.025 \, \Omega \):

\[ V_{PT}^{(theo)} = \frac{\pi}{2\sqrt{2}} \left( V_{out,DC} + 2 \cdot V_f + 2 \cdot R_f \cdot \frac{V_{out,DC}}{R_L} \right) = 7.92 \text{V} \]
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**Design Process**

Design of PT is application-related

Input Drivers:

Example of a DC-DC converter using a half-bridge inverter

Output Rectifiers

- Design Process
- Driving circuit topologies for PTs

**Design considerations**

Driving circuit topologies for PTs

- Class-E DC/AC converter
- Push-pull DC/AC converter
- Half-bridge DC/AC converter
- Full-bridge DC/AC converter
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**Design considerations**

Rectifying topologies for PTs

![Diagram of rectifying topologies for PTs]

**Ideal Waveform Assumption:** Voltage and Current Sine or Rectangular [Steigerwald 1988]

Summary output rectifying circuits [Lin 1997]

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**Design considerations - 1D Eq. circuit**

Rosen PT - $\lambda/2$ Operation

![Diagram of Rosen PT - $\lambda/2$ Operation]

For $\lambda/2$

$R_\text{in} = \frac{\omega L}{\omega L - \frac{\omega L}{\omega L + \omega L}} \frac{\omega L}{\omega L - \frac{\omega L}{\omega L + \omega L}}$
**Design considerations - 1D Eq. circuit**

**Determination of the PT parameters - Motional Branch**

The transformer is designed to provide maximum efficiency at the nominal load. This is achieved by selecting \( C_{d2} \) as:

\[
C_{d2} = \frac{1}{\omega_{res} \cdot R_{EQ}}
\]

The vibration velocity is equal to the motional current in the equivalent circuit, thus:

\[
i_m = v = \frac{\sqrt{P_{out,DC} \cdot 2 \cdot \omega_{res} \cdot C_{d2}}}{A_2}
\]

The number of secondary layers \( n_{out} \) and the force factor of the secondary section, \( A_2 \), are obtained using the following equations (case of radial PT):

\[
A_2 = \frac{n_{out} \cdot 2 \pi \cdot r \cdot d_{31,\text{out}}}{S_{11} \cdot (1 - \sigma)}
\]

\[
R = \frac{r_m}{A_2^2}, \quad L = \frac{L_m}{A_2^2}, \quad C = c_m \cdot A_2^2, \quad N = \frac{A_1}{A_2}
\]

**Material Characteristics limit the Power Density**

The number of secondary layers \( n_{out} \) and the force factor of the secondary section, \( A_2 \), are obtained using the following equations (iterative process):

\[
A_2 = \frac{n_{out} \cdot 2 \pi \cdot r \cdot d_{31,\text{out}}}{S_{11} \cdot (1 - \sigma)}
\]

\[
t_2 = \frac{t_{layer}}{n_{out}}, \quad t_{layer} = \frac{E_{33} \cdot (1 - k_{p,\text{out}}^2) \cdot \pi \cdot r^2 \cdot n_{out}}{C_{d2}}
\]
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**Design Process**

PTs are frequency and load dependents devices

\[
M_{PT} = \frac{V_{2,PT}}{V_{1,PT}} = N \left[ \left( \frac{1}{C_{L}} \frac{1}{C_{R}} \frac{1}{R_{P}} \frac{1}{C_{P}} \right) \left( \frac{1}{C_{C}} \frac{1}{C_{C}} \frac{1}{C_{C}} \frac{1}{C_{C}} \right) \right]^{1/2}
\]

\[
\omega_r = \frac{1}{\sqrt{L \cdot C}}
\]

**Simplified Equivalent Circuit of a PT**

Control above-resonance (inductive window)

**Design considerations**

**Inductor-Less Resonant Topologies**

- Larger PT Size
- No input inductance
- High-Side Drive
- Step-down
- PT input to GND

- CIT Challenge Award (ELC-00-006) “Linear Ballast Development”, Virginia Tech, founded by Face Electronics, Virginia, USA. 2000
- S. Bronstein and S. Ben-Yaakov, “Design considerations for achieving ZVS in a half bridge inverter that drives a piezo transformer with no series inductor”, IEEE APEC 2002
**Design considerations**

**Inductor-Less Resonant Topologies**

- The PT must be designed specifically to meet inductor-less.
- Very narrow input voltage control and output load control (use for fixed Vin and Rload applications)
- The lack of input inductance increases the size of the PT.

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**Design considerations - FEA Simulation**

**Advanced Modeling - FEA**

Equivalent circuits allow the optimization regarding efficiency, transfer ratio, load operation and integration with input and output circuitry. The equivalent circuit relates the size, material properties, and operation mode w/ the lumped elements in the eq. circuit.

FEA simulation is in general required to optimize the PT design. This is specially relevant in higher harmonic modes operation, as the coupling coefficient is strongly affected by the geometry and other modes. This is not easily determined w/ the equivalent circuit. FEA software include: ATILA, ANSYS, Piezo Plus, Femtet.
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Design considerations - FEA Simulation

Modeling and Design

Modal Analysis of the PT structure to determine spurious resonances (open circuit) determined by FEA simulation

Example of a FEA parameter optimization using FEA software.

<table>
<thead>
<tr>
<th>L x W x t</th>
<th>fr</th>
<th>fa</th>
<th>keff</th>
</tr>
</thead>
<tbody>
<tr>
<td>BT4</td>
<td>10.068</td>
<td>10.068</td>
<td>1.24</td>
</tr>
<tr>
<td>T3</td>
<td>10.241</td>
<td>10.241</td>
<td>0.00</td>
</tr>
<tr>
<td>BW2</td>
<td>13.083</td>
<td>13.083</td>
<td>0.00</td>
</tr>
<tr>
<td>T4</td>
<td>14.236</td>
<td>14.236</td>
<td>0.00</td>
</tr>
<tr>
<td>BT5</td>
<td>14.705</td>
<td>14.706</td>
<td>0.72</td>
</tr>
<tr>
<td>L1</td>
<td>17.345</td>
<td>17.766</td>
<td>21.65</td>
</tr>
<tr>
<td>T5</td>
<td>18.735</td>
<td>18.735</td>
<td>0.00</td>
</tr>
<tr>
<td>BT6</td>
<td>20.398</td>
<td>20.400</td>
<td>1.50</td>
</tr>
<tr>
<td>BW3</td>
<td>21.846</td>
<td>21.846</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Main mode of operation λ/2

The multi-impedance approach - Accurate 3D Eq. circuit

A single port or a multi-port piezo device can be exactly represented by a frequency-dependent matrix for ALL the frequencies.

\[
\begin{bmatrix}
I_1 \\
V_1 \\
\end{bmatrix}
= \begin{bmatrix}
Y_{11}(f) & Y_{12}(f) \\
Y_{21}(f) & Y_{22}(f) \\
\end{bmatrix}
\begin{bmatrix}
I_2 \\
V_2 \\
\end{bmatrix}
\]

If a load \( Y_L \) is connected in the output:

\[
I_2(f) = \frac{-V_2(f) \cdot Y_L(f)}{-Y_21(f) + Y_L(f)}
\]

Voltage Gain:

\[
\frac{V_2(f)}{V_1(f)} = \frac{-Y_21(f)}{-Y_22(f) + Y_L(f)}
\]
Design considerations - FEA Simulation

The multi-impedance approach - Accurate 3D Eq. circuit

Once the multi-impedance is obtained, calculation of any load condition will take just seconds.

The impedance matrix can be used in PSpice to have a “3D” equivalent model of the PT as accurate as the FEA simulation is.
Piezoelectric Transformers: Applications

LCD Backlighting, Power Converters, Fluorescent Ballasts

5W DC/AC (Vin: 8-20V; Out: 500-800V)
CCFL Backlighting, (>10 Million/Year worldwide)

15W Automotive LED Driver
(Vin: 6-20V; Vout: 15V)

110V/32W Piezoelectric Fluorescent Ballast

3W AC/DC Power Supply (Vin: 80-450V; Out: 6V)
Cellular Phone Battery Charger, Off-line LED driver

35W AC/DC Converter (Vin: 80-450V; Vout: 20V)
Laptop Adapter

110V/15W Compact Fluorescent Lamp (CFL) Ballast

PROPRIETARY INFORMATION

Micromechatronics, Inc.

Commercial Step-up Piezo Converters

Piezo-Converters for CCFL Backlighting: M1-Inverter

**SPECIFICATIONS - M1 Inverter**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size (mm)</td>
<td>80.33 x 15.75 x 4.75</td>
</tr>
<tr>
<td>Main Power</td>
<td>8 - 20 VDC</td>
</tr>
<tr>
<td>Operating Frequency</td>
<td>51-53 KHz</td>
</tr>
<tr>
<td>Start-up Voltage at 25°C</td>
<td>1.5 - 1.7 kVrms</td>
</tr>
<tr>
<td>Running Voltage</td>
<td>615 Vrms</td>
</tr>
<tr>
<td>Audible noise (*)</td>
<td>&lt; 35dB</td>
</tr>
<tr>
<td>Frequency PWM dimming</td>
<td>200-220Hz</td>
</tr>
<tr>
<td>Brightness control PWM %</td>
<td>21% to 100%</td>
</tr>
<tr>
<td>Rise/Fall time of (I_{on}) in burst mode</td>
<td>150 µs</td>
</tr>
<tr>
<td>Shock and Vibration (3-axis)</td>
<td>50 G’s</td>
</tr>
<tr>
<td>MTBF</td>
<td>50,000 hours</td>
</tr>
</tbody>
</table>

**Features**

- Inherent high gain at no load, that provides the lamp ignition voltage.
- Load dependent gain that avoids the use of ballast capacitor in series with the CCFL lamp.
- Absence of leadage magnetic field.
- High Q factor, that gives low distorted sinusoidal lamp current waveform.
- Small size and weight.
- High reliability due to the absence of a high voltage secondary winding.

**PROPRIETARY INFORMATION**

Micromechatronics, Inc.

Apple G4 Powerbook
Micromechatronics, Inc. introduces the word first High Voltage Piezoelectric Converter product line. Three new reference DC-DC converters are introduced: 2kVdc/4W; 5kVdc/5W; 10kVdc/5W. The converters are operated under input voltages of 8 to 14Vdc. The converters are fully regulated against changes of the input voltage and the output load. Furthermore, the output voltage can be programmed from 0 to 100% through a control 0 - 2.1V control pin.

This new technology uses magnetic-less, low profile, high efficiency and high power density high voltage piezoelectric transformers. Developed through many years of research, development and commercialization of piezoelectric technology, the new converters provide the most compact and efficient high voltage converting solution.

### Specifications

<table>
<thead>
<tr>
<th>PRODUCT</th>
<th>RESULTS</th>
<th>FEATURES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>95 mm x 19 mm (w/ connectors)</td>
<td>Miniature, Surface Mount Construction</td>
</tr>
<tr>
<td>Input Voltage (DC)</td>
<td>8 V to 14 V</td>
<td>Use of Magnetic-less Transformer Technology</td>
</tr>
<tr>
<td>Output Voltage (DC)</td>
<td>2 kV</td>
<td>Output Power: 4 W max</td>
</tr>
<tr>
<td>Max Output Power (W)</td>
<td>4 W</td>
<td>Wide Input Voltage Regulation (8 Vdc to 14 Vdc)</td>
</tr>
<tr>
<td>Max. Efficiency (%)</td>
<td>&gt; 82 %</td>
<td>0 to 100% Output Programmable</td>
</tr>
<tr>
<td>Control voltage</td>
<td>0 to 2.1 V to reach 0 to 2 kV</td>
<td>Output Short Circuit and Over Voltage Protected</td>
</tr>
</tbody>
</table>

#### Input Voltage Connector

- **SM06B-SRSS-TB**: 6 pins

#### Output Voltage Connector

- **SM02B-BHSS-1**: 2 pins

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Ultrasonic Piezoelectric Transformers
for Power Conversion

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2 kV - 4W DC-DC Piezoelectric Converter

- **Input Voltage Connector**: SKX360-SRSS-TB 6 pins
- **Piezoelectric Transformer**: B5X360-5000-1 2 pins
- **Output Voltage Connector**: PDK50-8000-1 2 pins
Ultrasonic Piezoelectric Transformers for Power Conversion

Military and Space Applications

Opportunities for Space Applications

SOLAR ARRAY

REGULATOR

DC/DC CONVERTER

REGULATED BUS

BATTERY CHARGER (DC/DC CONVERTER)

DARPA-SBIR Phase I, (2003-4)

PAYLOAD DC/DC CONVERTER MODULES

COMUNICATION PAYLOADS

DETECTORS, SENSORS, ETC

BATTERY BANK

NASA-SBIR Phase II, (2002-4)

PROPRIETARY INFORMATION

Military and Space Applications

TWT High Voltage DC/DC multi-output power supply

Agency: NASA

Application: Small Satellite Communication

Goal: Development of a piezo-power supply for Traveling Wave Tube amplifier (TWTA)

TWT-Power Supply Prototype:
Cathode (4kV/ 15W); Two collectors (1.5kV/10W, and 800V/40W total).

Detail of the cathode power supply
Military and Space Applications

Pulsed Plasma Thruster Discharge Initiation (DI) System

Agency: NASA
Application: Small Satellite Propulsion
Goal: Integrated high reliability discharge initiation (DI) system for a Pulsed Plasma Thruster

Piezoelectric discharge initiation system using an IGBT solid state switch

Experimental set-up used to evaluate the D.I., under full vacuum conditions (9.1x10^-7 torr) at NASA Glenn facilities.

Discharge current: 78.4 Apk (CH2);
Discharge voltage: 2.08 kV (CH1)
Military and Space Applications

**DC/DC Piezo Converter for Satellite Power Bus**

Developed for DARPA under a SBIR contract

**Application:** Small Satellite Point of Load converter

**Goal:** Replacement of magnetic transformer by more efficient, compact and powerful piezoelectric transformers

![DC-DC piezo-converter developed by Face](image)

**DC/DC piezo-converter developed by Face**

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**Ultra High Voltage DC-DC Piezo-converters**

**100kV/20W Piezo Supply for Neutron Source Generator**

Modal Analysis of the PT structure to determine spurious resonances (open circuit) determined by FEA simulation

- BT4 10.080 kHz
- T3 10.245 kHz
- BW2 13.262 kHz
- T4 14.240 kHz
- BT5 14.710 kHz
- T5 18.750 kHz
- BT6 20.433 kHz
- BW4 22.130 kHz
- L1 17.865 kHz

![Main mode of operation](image)
Ultra High Voltage DC-DC Piezo-converters

100kV/20W Piezo Supply for Neutron Source Generator

Results of the modal analysis for the new very high voltage PT (fr = resonance frequency; fa = antiresonance frequency; keff = effective coupling coefficient)

<table>
<thead>
<tr>
<th></th>
<th>L x W1 x H</th>
<th>L x W2 x H</th>
<th>L x W3 x H</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>fr</td>
<td>fa</td>
<td>keff</td>
</tr>
<tr>
<td>BT4</td>
<td>10.015</td>
<td>10.015</td>
<td>0.88</td>
</tr>
<tr>
<td>T3</td>
<td>12.853</td>
<td>12.853</td>
<td>0.00</td>
</tr>
<tr>
<td>BW2</td>
<td>10.842</td>
<td>10.842</td>
<td>0.00</td>
</tr>
<tr>
<td>T4</td>
<td>17.349</td>
<td>17.775</td>
<td>0.72</td>
</tr>
<tr>
<td>BT5</td>
<td>14.638</td>
<td>14.638</td>
<td>15.94</td>
</tr>
<tr>
<td>L1</td>
<td>17.349</td>
<td>17.574</td>
<td>15.00</td>
</tr>
<tr>
<td>T5</td>
<td>22.625</td>
<td>22.625</td>
<td>0.00</td>
</tr>
<tr>
<td>BT6</td>
<td>20.331</td>
<td>20.333</td>
<td>1.51</td>
</tr>
<tr>
<td>BW3</td>
<td>18.833</td>
<td>18.833</td>
<td>0.00</td>
</tr>
</tbody>
</table>

The stronger vibration mode to allow energy conversion is the longitudinal mode, L1. When the width size is W1, the Bending Transversal BT5 mode is very close from the longitudinal, thus decreasing its coupling coefficient. By modifying the width size to W2 and W3, it is possible to separate the BT5 spurious mode and improve the coupling of the longitudinal mode, which is the one of interest.

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37
Ultra High Voltage DC-DC Piezo-converters

100kV/20W Piezo Supply for Neutron Source Generator

Single layer piezoelectric design reduces the prototyping time and allows a very early confirmation of the validity of the FEA simulation results. However, single layer design requires a very high input voltage (200-500Vrms in our case).

MULTILAYER PIEZOELECTRIC TRANSFORMERS were designed and manufactured following the external size of the single layer tested to reduce the input voltage requirements to a "battery-level voltage".

Internal layer design of the multilayer piezoelectric transformer
Ultrasonic Piezoelectric Transformers for Power Conversion

**Ultra High Voltage DC-DC Piezo-converters**

**100kV/20W Piezo Supply for Neutron Source Generator**

**6kV/20W High Voltage Multi-Layer Piezo Transformers**

Different manufacturing batches needed to optimize the sintering process. Due to the length of the unit, very long co-firing process was required before successful sintering.

**Characterization Multilayer PTs Sample: P=20W / Vout=5kV**

- Frequency to Step-up ratio
- Efficiency (%)
- Vibration speed [m/s]
- Rise Temp [°C]

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Ultrasonic Piezoelectric Transformers for Power Conversion

Ultra High Voltage DC-DC Piezo-converters

100kV/20W Piezo Supply for Neutron Source Generator

Construction and Testing of the DC-DC Converter

Output multiplier circuit

Testing the PT with the output circuit

DC-DC Converter before encapsulation

Test in dielectric oil bath under different load

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Operation characteristics of the 100 kV ultra high voltage power supply

Voltage control characteristic under a fix input voltage of 22 V

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Piezoelectric Transformers: Trends

“Small PTs” - Sub 0.5-mm³ structures - MEMS-based PTs

MEMS-PTs are still at feasibility demonstration level. Developments are mainly toward manufacturing issues rather than performance evaluation. Many designs are operating at “low” frequencies in a bending mode (very inefficient). Multilayer Process is still an issue to resolve. Interdigital electrodes has been used in some structures.

Vasic et. al (2004)
Frequency=45.4 kHz, 185 kHz
Thickness: Silicon(6um), PZT(4um)
Radius=750um
Gain=1/10 at 45.4 kHz
0.25uW under 5V

Kim et. al (2006)
1000x400x5.8 um³
PZT = 0.4um
IDT Output
Gain = 2.1
at 8 kHz with 1MΩ

Wang et. al (2007)
Radius=750um
Thickness: Silicon(8um); PZT(8um)
Gain= 0.38 at 95.5 kHz

Micromechatronics, 2009
Floating Structure Operation in contour mode
Higher Efficiency

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