PROPRIETARY INFORMATION

Ultrasonic Piezoelectric Transformers for Power Conversion

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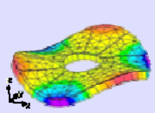
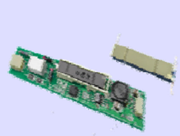
Introduction to MMech

- 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
- Spin-offs: M-Mech Defense, Inc. (2009)

Product Portfolio			
Design Software	Motion Control	Energy Conversion	Industrial Equipment
ATILA FEA Software, GiD Pre/Post Processor	Piezo Elements, Actuators, Stages, Ultrasonic Motors	Piezo Generators, Piezo Transformers	Ultrasonic Cleaning, Cutting, Measuring
			

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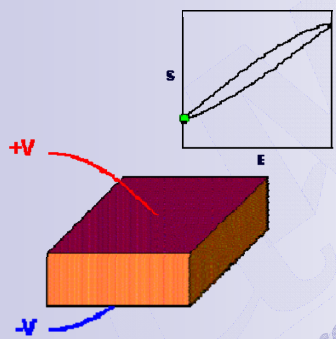
Piezoelectric Transformers: Background

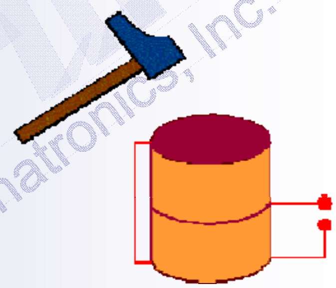
Piezoelectricity - Basics

INVERSE PIEZOELECTRIC EFFECT



Electrical to Mechanical energy conversion

DIRECT PIEZOELECTRIC EFFECT



Mechanical to Electrical energy conversion

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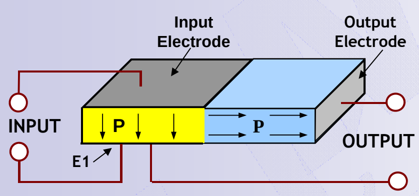
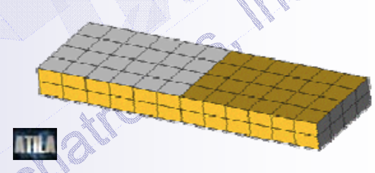
Piezoelectric Transformers: Background

What a Piezoelectric Transformer is?

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.



Rosen-Type Piezoelectric Transformer



Operation of a "Lambda/2" Piezoelectric Transformer

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

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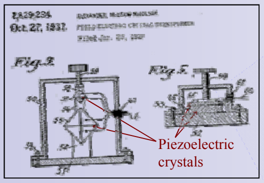
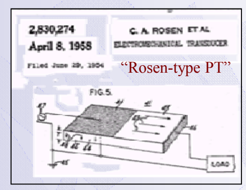
Piezoelectric Transformers: Background

Historical Background - High Voltage conversion

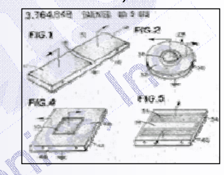
1927 First Studies. Alexander M. Nicolson proposed some basic PTs using Rochelle salt crystals.



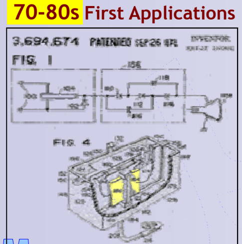
1954 Rosen-PT. First Piezo "Ceramic" Transformer.

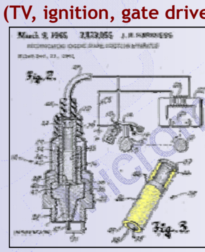


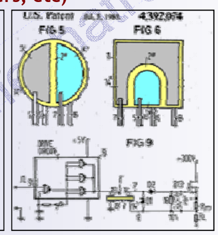
1960 New Designs. H.Jaffe, D.A.Berlincourt followed w/ new designs (ex. Unipoled radial and contour-mode PTs)



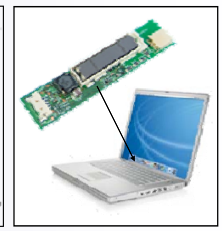
70-80s First Applications (TV, ignition, gate drivers, etc)







90s CCFL Backlighting



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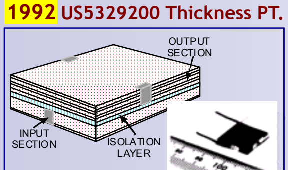
Piezoelectric Transformers: Background

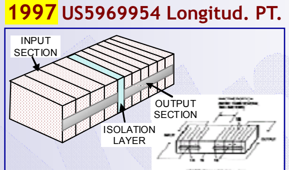
Historical Background - "Step-down" Power PTs

1992 US5329200 Thickness PT.



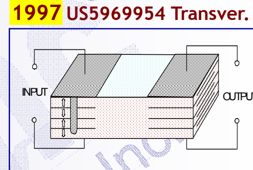
Thickness vibration mode
Thickness Polarization
Res. Freq: ~ 1MHz

1997 US5969954 Longitud. PT.



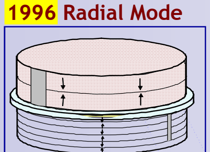
Longitudinal vibration mode
Longitudinal Polarization
Res. Freq: ~ 100kHz

1997 US5969954 Transver. PT.



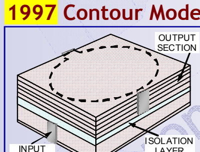
Longitudinal vibration mode
Transversal Thickness Polarization
Res. Freq: ~ 100kHz

1996 Radial Mode



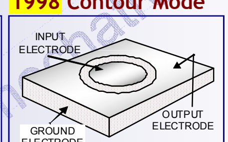
Radial Vibration Mode
Thickness Polarization
Res. Freq: ~ 50-250kHz

1997 Contour Mode



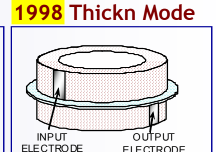
Contour Vibration Mode
Thickness Polarization
Res. Freq: ~ 50-250kHz

1998 Contour Mode



Contour Vibration Mode
Thickness Polarization
Res. Freq: ~ 50-100kHz

1998 Thickn Mode



Thickness Vibration Mode
Thickness Polarization
Res. Freq: ~ 400kHz

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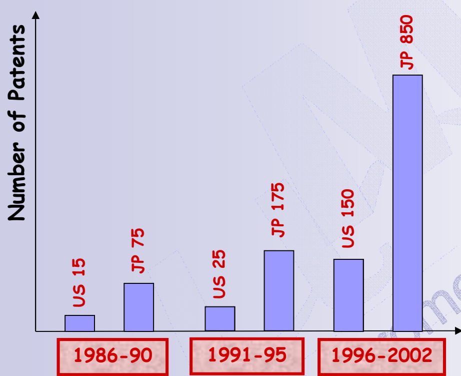
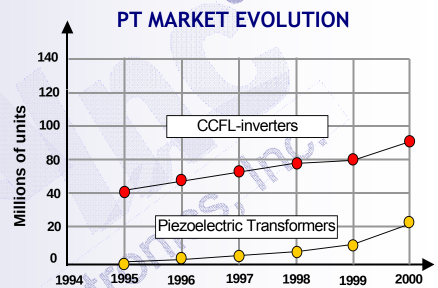
Piezoelectric Transformers: Background

Historical Background





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

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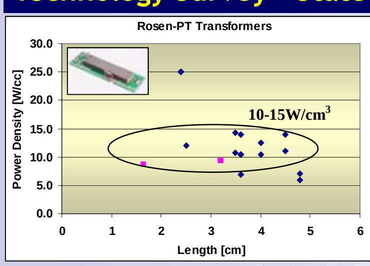
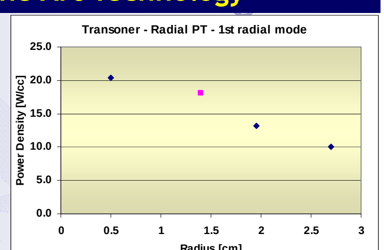
Piezoelectric Transformers: Background

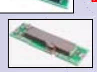
Technology Survey - State of the Art Technology





20W / 4kV
100^L x 20^W x 3.6^t (mm)
7200 mm^3

5W / 1kV
32^L x 6.75^W x 2.5^t (mm)
540 mm^3

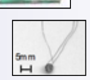


1W / 1kV
16.5^L x 4.25^W x 1.65^t (mm)

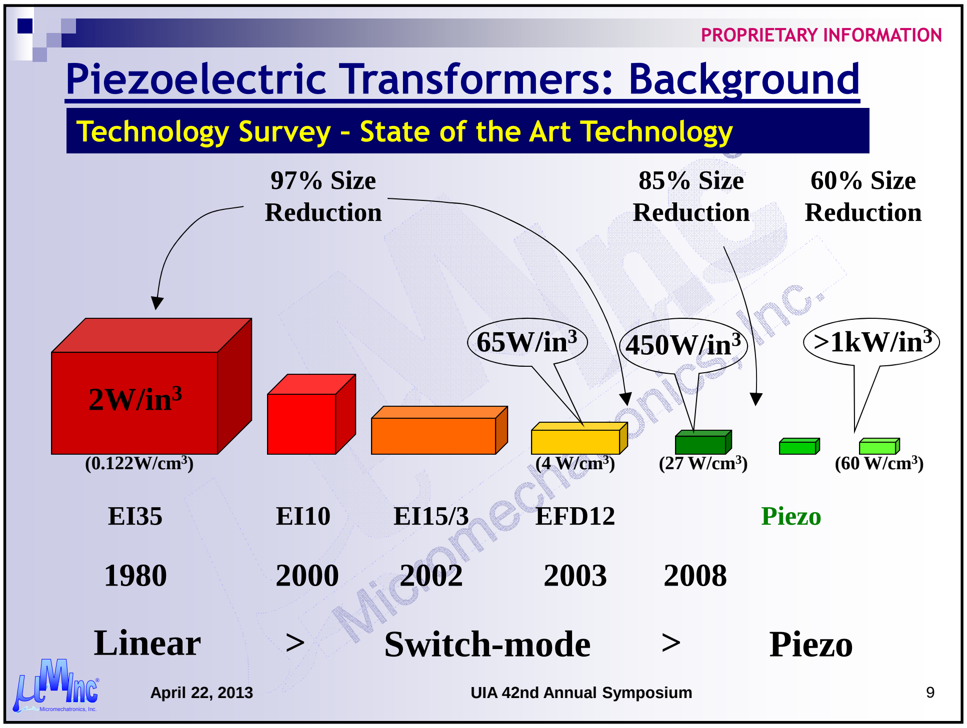
12.6^L x 1.5^W x 0.5^t (mm)
9.45 mm^3

35W / 15V
27^D x 6.1^t (mm) 3492 mm^3
Step-down PT

15W / 15V
19^D x 3.81^t (mm) 1138 mm^3
Step-down PT



0.4W / 120V
5^D x 1.0^t (mm) 19.6 mm^3
Step-up PT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Piezoelectric Transformers: Background
Technology Survey - State of the Art Technology
97% Size Reduction
85% Size Reduction
60% Size Reduction
2W/in³
(0.122W/cm³)
65W/in³
(4 W/cm³)
450W/in³
(27 W/cm³)
>1kW/in³
(60 W/cm³)
EI35
EI10
EI15/3
EFD12
Piezo
1980
2000
2002
2003
2008
Linear > Switch-mode > Piezo
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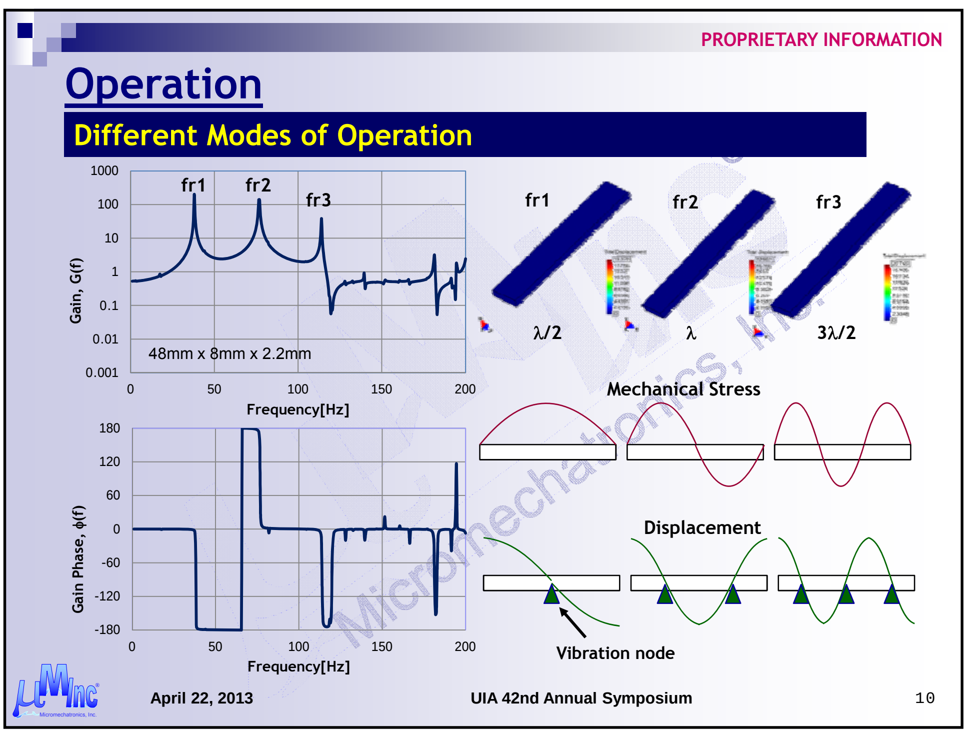
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Operation
Different Modes of Operation
fr1
fr2
fr3
Gain, G(f)
1000
100
10
1
0.1
0.01
0.001
48mm x 8mm x 2.2mm
0
50
100
150
200
Frequency[Hz]
Gain Phase, φ(f)
180
120
60
0
-60
-120
-180
λ/2
λ
3λ/2
Mechanical Stress
Displacement
Vibration node
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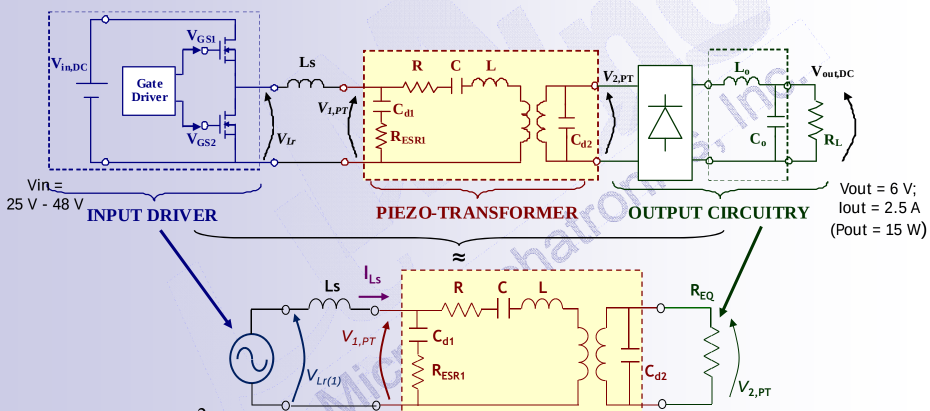
Design Process

Obtain the inverter and load model

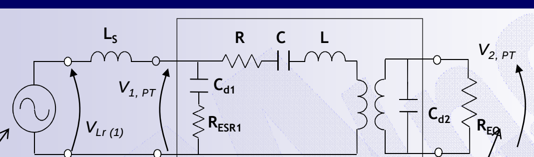
The design of a PT for an specific application involves the consideration of the input and output circuitry.



$$V_{Lr(1)}(t) = \frac{2}{\pi} \cdot V_{IN} \cdot \sin(\pi \cdot D) \cdot \sin(\omega t)$$

Design Process

Equivalent circuit to determine the PT in/out specs.



(Full bridge)

$$V_{Lr(1)}(t) = \frac{2}{\pi} \cdot V_{IN} \cdot \sin(\pi \cdot D) \cdot \sin(\omega t) \qquad R_{EQ} = \frac{\pi^2}{8} \cdot R_L \cdot \left(1 + \frac{2 \cdot V_F}{V_{DC}} + \frac{2 \cdot R_F}{R_L}\right)$$

Example: $V_{out,DC}$ = 6 V; I_{out} = 2.5 A (Pout = 15 W); Vin = 25 – 40 Vdc ➡ RL_dc = 2.4 Ω

Assuming V_F=0.5V and R_F=0.025 Ω:

$$R_{EQ} = \frac{\pi^2}{8} \cdot R_L \cdot \left(1 + \frac{2 \cdot V_F}{V_{DC}} + \frac{2 \cdot R_F}{R_L}\right) = 3.52\Omega$$

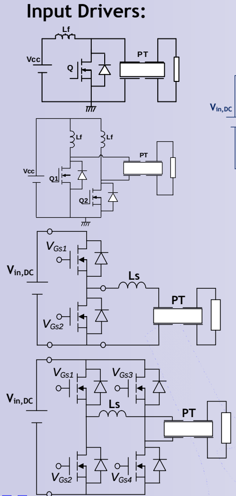
$$V_{2,PT\,(RMS)} = \frac{\pi}{2 \cdot \sqrt{2}} \cdot \left(V_{out,DC} + 2 \cdot V_F + 2 \cdot R_F \cdot \frac{V_{out,DC}}{R_L}\right) = 7.92V$$

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

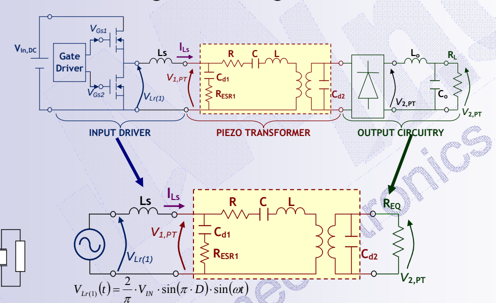
Design Process

Design of PT is application-related

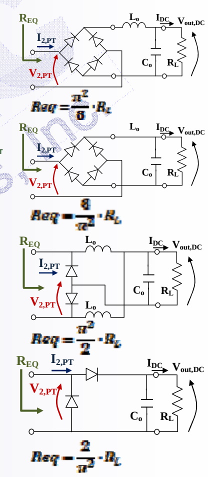
Input Drivers:



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

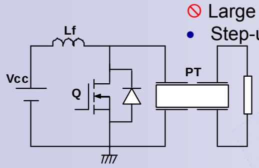


Output Rectifiers



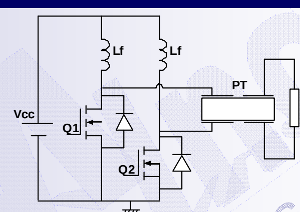
Design considerations

Driving circuit topologies for PTs



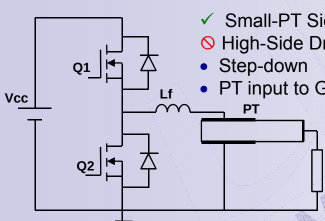
- ✓ Smaller PT Size (*L*)
- ⦸ Large Inductor *Lf*
- • Step-up or - down

Class-E DC/AC converter



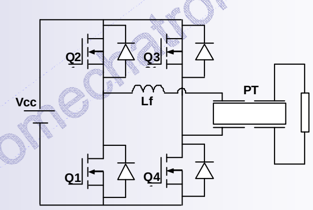
- ✓ Low-Side-Drive
- ✓ Smaller PT Size (*L*)
- ⦸ Two inductors *Lf*
- • Step-up

Push-pull DC/AC converter



- ✓ Small-PT Side (*L*)
- ⦸ High-Side Drive
- • Step-down
- • PT input to GND

Half-bridge DC/AC converter



- ✓ Small-PT Side (*L*)
- ✓ Constant frequency Phase Control
- ⦸ High-Side-Drive
- ⦸ Four Switches
- • Step-down or -up

Full-bridge DC/AC converter

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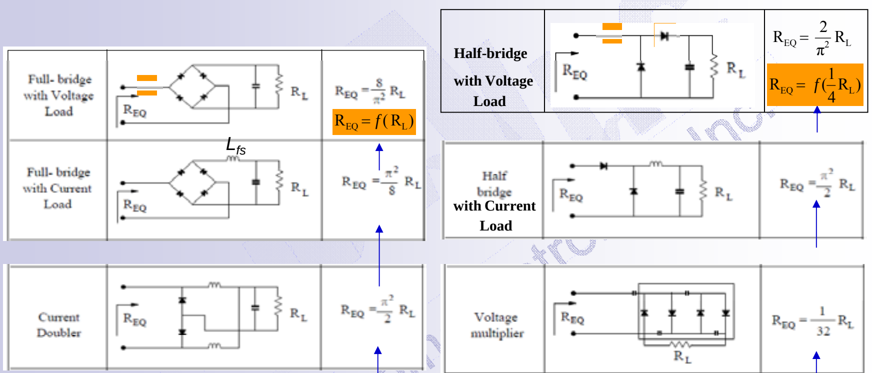
Design considerations

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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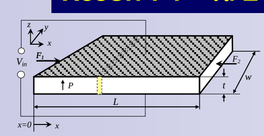
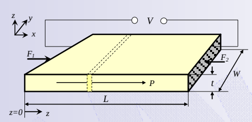
Design considerations - 1D Eq. circuit

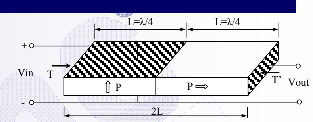
Rosen PT - λ/2 Operation



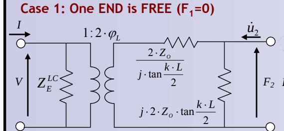
Case 1: One END is FREE (F_1=0)

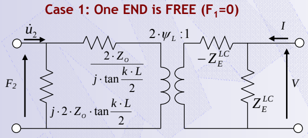


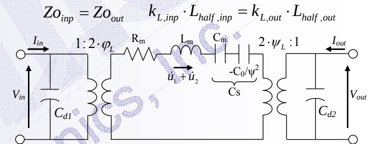
Case 1: One END is FREE (F_1=0)



$Zo_{inp} = Zo_{out}$ $\quad k_{L,inp} \cdot L_{half,inp} = k_{L,out} \cdot L_{half,out}$







$$Z_0 = \frac{k\cdot A}{\omega\cdot s_{11}^E} = \frac{k\cdot w.t}{\omega\cdot s_{11}^E} = \frac{\omega\cdot t\cdot w}{\sqrt{\frac{1}{\rho\cdot s_{11}^E}}\cdot s_{11}^E\cdot\omega} = \sqrt{\frac{\rho}{s_{11}^E}}\cdot t\cdot w$$

$$\vec{Z}_E^{LC} = \frac{t}{j\cdot\omega\cdot\varepsilon_{33}^T\cdot(1-k_{31}^2)\cdot w\cdot L} = \frac{1}{j\cdot\omega\cdot C_{d1}}$$

$$(v_L^E)^2 = \frac{1}{\rho\cdot s_{11}^E} \qquad \varphi_L = \frac{w\cdot d_{31}}{s_{11}^E}$$

$$k_{31}^2 = \frac{d_{31}^2}{s_{11}^E\cdot\varepsilon_{33}^T} \qquad k_L = \frac{\omega}{\upsilon_L^E} = \frac{2\pi}{\lambda}$$

$$\varepsilon_{33}^{LS} = \varepsilon_{33}^T\cdot(1-k_{31}^2)$$

$$Z_O = \frac{k\cdot A}{\omega\cdot s_{33}^D} = \frac{k\cdot t\cdot w}{\omega\cdot s_{33}^D} = \frac{\omega\cdot t\cdot w}{\sqrt{\frac{1}{\rho\cdot s_{33}^D}}\cdot s_{33}^D\cdot\omega} = \sqrt{\frac{\rho}{s_{33}^D}}\cdot t\cdot w$$

$$Z_E^{LC} = \frac{L}{j\cdot\omega\cdot\varepsilon_{33}^T\cdot(1-k_{33}^2)\cdot t\cdot w} = \frac{1}{j\cdot\omega\cdot C_{d2}}$$

$$(v_L^D)^2 = \frac{1}{\rho\cdot s_{33}^D} \qquad \psi_L = \frac{g_{33}}{\omega\cdot s_{33}^D}\cdot\frac{1}{Z_E^{LC}}$$

$$k_{33}^2 = \frac{d_{33}^2}{s_{33}^E\cdot\varepsilon_{33}^T} \qquad k_L = \frac{\omega}{v_L^D} = \frac{2\pi}{\lambda}$$

$$\varepsilon_{33}^{LS} = \varepsilon_{33}^T\cdot(1-k_{33}^2)$$

$$R_m = \frac{\omega\cdot L_1}{Q_m} = \frac{\pi\cdot Z_0}{2\cdot Q_m} = \frac{\omega}{Q_m}\cdot\frac{Mass}{2}$$ **for λ/2**

$$L_m = \frac{1}{C_1\cdot\omega_0^2} = \frac{\pi\cdot Z_0}{2\cdot\omega_0} = \frac{w\cdot t\cdot L\cdot\rho}{2} = \frac{Mass}{2}$$

$$C_m = \frac{2}{\omega_0\cdot\pi\cdot Z_0} = \frac{2\cdot L\cdot s_{33}^D}{\pi^2\cdot w\cdot t}$$

$$Cs = \frac{-C_1\cdot C_0}{(\psi_L)^2\cdot\left[C_1-\frac{C_0}{(\psi_L)^2}\right]} = \frac{C_1\cdot C_0}{C_0-C_1\cdot(\psi_L)^2}$$

$$(v_L)^2 = \left(\frac{0.5}{s_{11}^E}+\frac{0.5}{s_{33}^D}\right)\cdot\frac{1}{\rho}$$

PROPRIETARY INFORMATION

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:

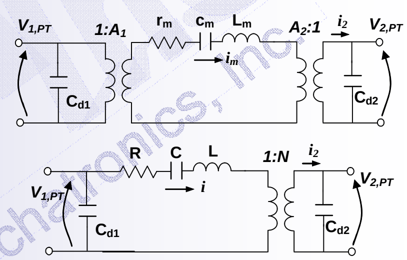
$$C_{d2} = \frac{1}{\omega_{res} \cdot R_{EQ}}$$

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):

$$A_2 = \frac{n_{out} \cdot 2\pi \cdot r \cdot d_{31,out}}{s_{11}^E \cdot (1-\sigma)}$$



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

PROPRIETARY INFORMATION

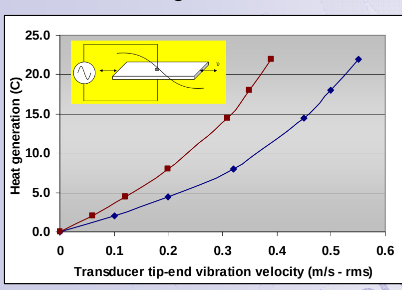
Design considerations - 1D Eq. circuit

Material Characteristics limit the Power Density

Depends on PT material, mode of operation, transformer design

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

Given by application needs



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**):

$$A_2 = \frac{n_{out} \cdot 2\pi \cdot r \cdot d_{31,out}}{s_{11}^E \cdot (1-\sigma)}$$

$$t_{2,layer} = \varepsilon_{33}^T \cdot \left(1 - k_{p,out}^2\right) \cdot \frac{\pi \cdot r^2 \cdot n_{out}}{C_{d2}}$$

$$t_2 = t_{2,layer} \cdot n_{out}$$

Manufacturing Limit

The value of the maximum vibration velocity is selected such as the temperature increase of the transformer does not exceed 25-30 ºC.

PROPRIETARY INFORMATION

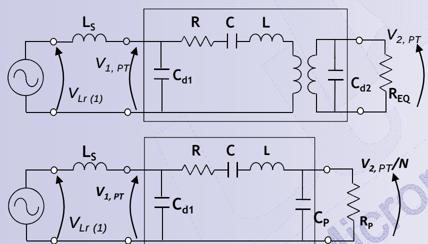
Design Process

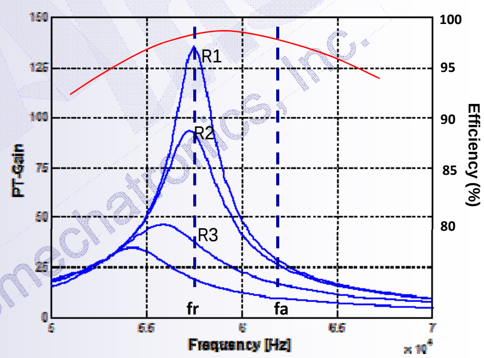
PTs are frequency and load dependents devices

$$M_{PT}=\frac{V_{2,PT}}{V_{1,PT}}=N\cdot\left\{\left[\left(1+\frac{C_P}{C}+\frac{r}{R_P}\right)-\left(1+\frac{C_P}{C}\right)\cdot\left(\frac{\omega}{\omega_o}\right)^2\right]^2+\left[\frac{\omega L}{R_P}-\frac{C_P}{\omega\cdot R_P\cdot C_o\cdot(C+C_P)}+\omega R_P C_o\frac{C_P}{C}\left(1+\frac{C_P}{C}\right)\right]^2\right\}^{1/2}$$

$$C_P=N^2\cdot C_{d2}\qquad R_P=\frac{R_{EQ}}{N^2}$$

$$\omega_o=\frac{1}{\sqrt{L\cdot C_o}}\qquad C_o=\frac{C\cdot C_P}{C+C_P}$$





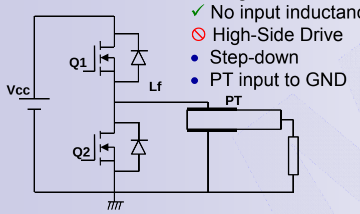
Simplified Equivalent Circuit of a PT — Control above-resonance (inductive window)

PROPRIETARY INFORMATION

Design considerations

Inductor-Less Resonant Topologies

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



Linear Ballast

Linear Ballast with Power Factor Correction

CIT Challenge Award (ELC-99-007) "Transoner Characterization", **Virginia Tech**, founded by **Face Electronics**, Virginia, USA. 1998

CIT Challenge Award (ELC-00-006) "Linear Ballast Development", Virginia Tech, founded by Face Electronics, Virginia, USA. 2000

R.-L. Lin, "Piezoelectric Transformer Characterization and Application of Electronic Ballast ," PhD Thesis, Virginia Tech, USA 2001.

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

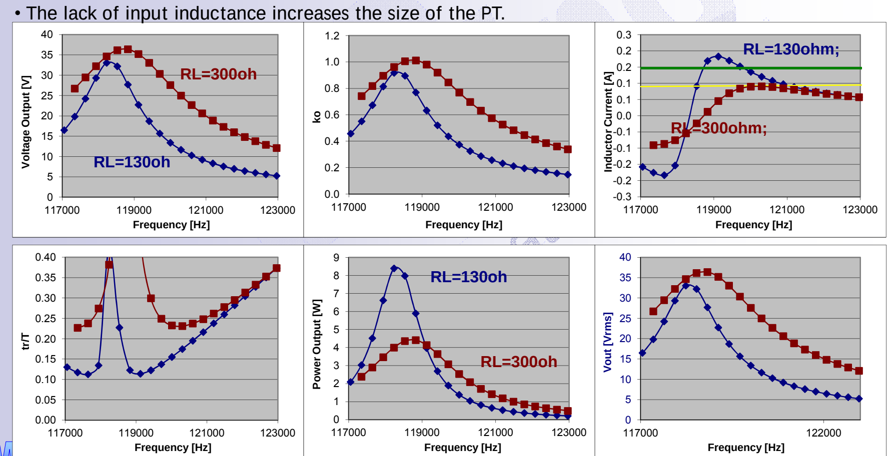
M.Sanz, P.Alou, R.Prieto, J.A.Cobos, J.Uceda, "Comparison of different alternatives to drive piezo transformers, IEEE APEC 2002.

PROPRIETARY INFORMATION

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.

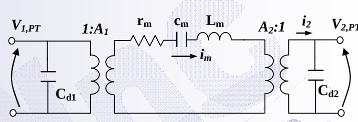


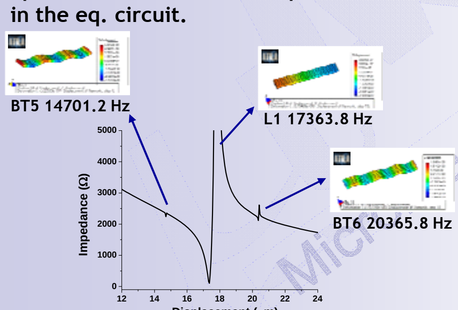
PROPRIETARY INFORMATION

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.

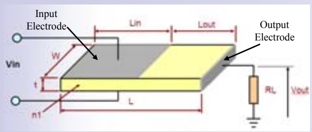




FEA simulation is in general required to optimize the PT design. This is specially relevant in higher harmonic modes operation, as the coupling coefficient is strongly affected by the geometry and other modes. This is not easily determined w/ the equivalent circuit. FEA software include: ATILA, ANSYS,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

Design considerations - FEA Simulation

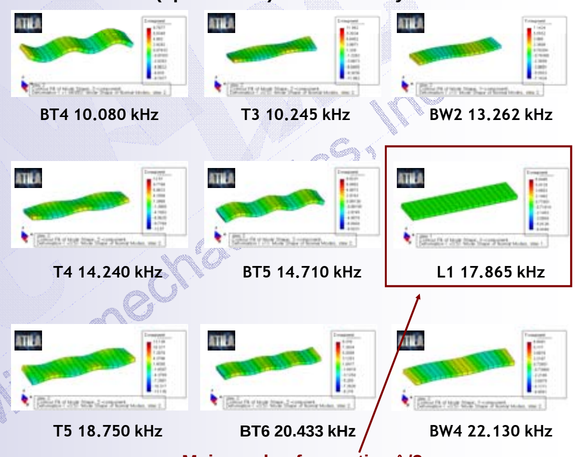
Modeling and Design



Example of a FEA parameter optimization using FEA software.

	L x W x t		
	fr	fa	keff
BT4	10.068	10.068	1.24
T3	10.241	10.241	0.00
BW2	13.083	13.083	0.00
T4	14.236	14.236	0.00
BT5	14.705	14.706	0.72
L1	17.345	17.766	21.65
T5	18.735	18.735	0.00
BT6	20.398	20.400	1.50
BW3	21.846	21.846	0.00

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



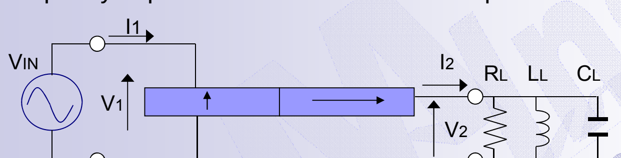
Main mode of operation λ/2

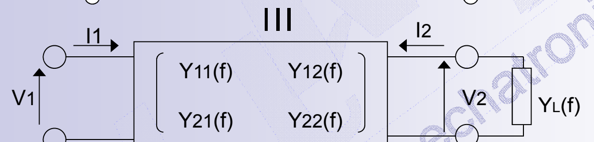
PROPRIETARY INFORMATION

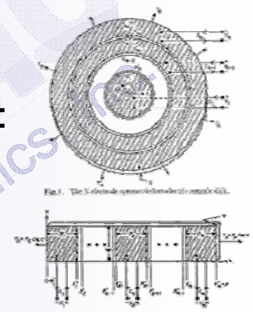
Design considerations - FEA Simulation

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

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







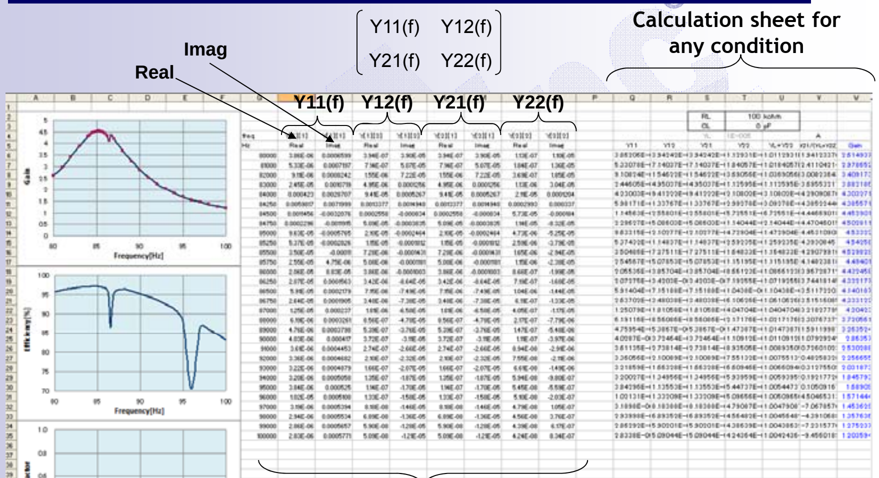
If a load YL is connected in the output: I2 (f) = -V2 (f) * YL (f)

Voltage Gain: $\frac{V2\,(f)}{V1\,(f)} = \frac{-Y21(f)}{Y22(f) + YL\,(f)}$

PROPRIETARY INFORMATION

Design considerations – FEA Simulation

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



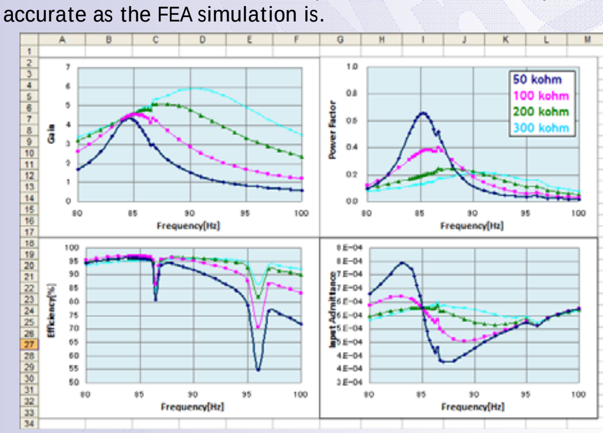
PROPRIETARY INFORMATION

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.

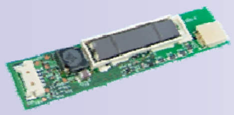
The impedance matrix can be used in PSpice to have a “3D” equivalent model of the PT as accurate as the FEA simulation is.



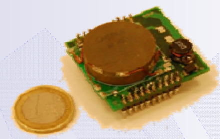
PROPRIETARY INFORMATION

Piezoelectric Transformers: Applications

LCD Backlighting, Power Converters, Fluorescent Ballasts

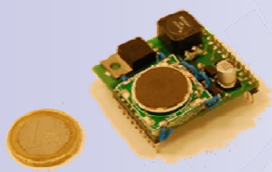


5W DC/AC (Vin: 8-20V; Out: 500-800V)
CCFL Backlighting.
(>10Million/Year worldwide)

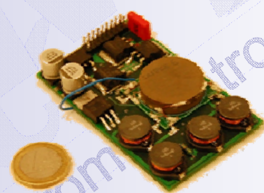


15W Automotive LED Driver
(Vin: 6-20V; Vout:15V)

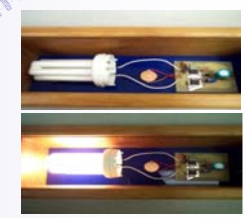
110V/32W Piezoelectric Fluorescent Ballast



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

Commercial Step-up Piezo Converters

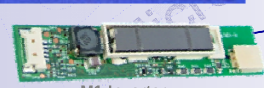
Piezo-Inverters for CCFL Backlighting: M1-Inverter

SPECIFICATIONS - M1 Inverter	
Size (mm)	80.33 x 15.75 x 4.75
Main Power	8 - 20 VDC
Operating Frequency	51-53 kHz
Start-up Voltage at 25ºC	1.3-1.7 kVrms
Running Voltage	615 Vrms
Audible noise (*)	< 35dB
Frequency PWM dimming	200-220Hz
Brightness control PWM %	21% to 100%
Rise/Fall time of I_{lamp} in burst mode	150 µs
Shock and Vibration (3-axis)	50 G's
MTBF	50,000 hours

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 leadkage 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.

Q-16 Inverter



M1-Inverter

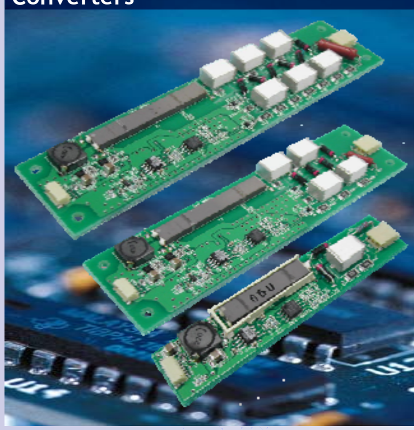
Apple G4 Powerbook

PROPRIETARY INFORMATION

Commercial Step-up Piezo Converters

Word First Piezoelectric DC-DC Converters

High Voltage Piezoelectric DC-DC Converters



Word First Piezoelectric DC-DC Converter

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.

PROPRIETARY INFORMATION

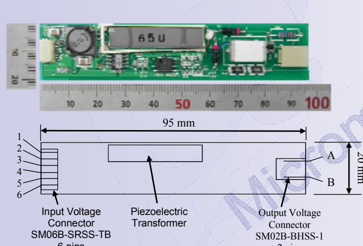
Commercial Step-up Piezo Converters

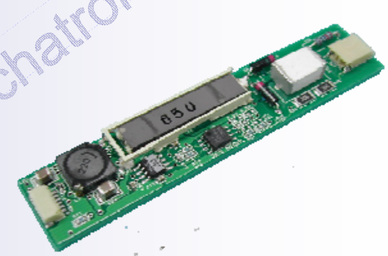
2 kV - 4W DC-DC Piezoelectric Converter

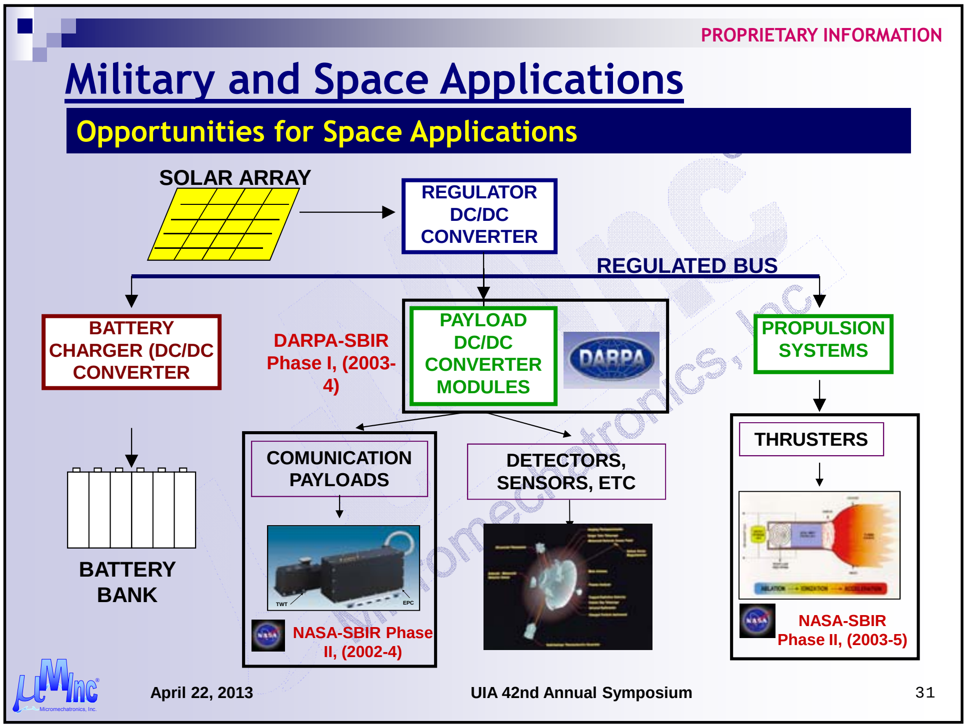
SPECIFICATIONS	
PRODUCT	RESULTS
Size	95 mm x 19 mm (w/ connectors)
Input Voltage (DC)	8 V to 14 V
Output Voltage (DC)	2 kV
Max Output Power (W)	4 W
Max. Efficiency (%)	> 82 %
Control voltage	0 to 2.1 V to reach 0 to 2 kV

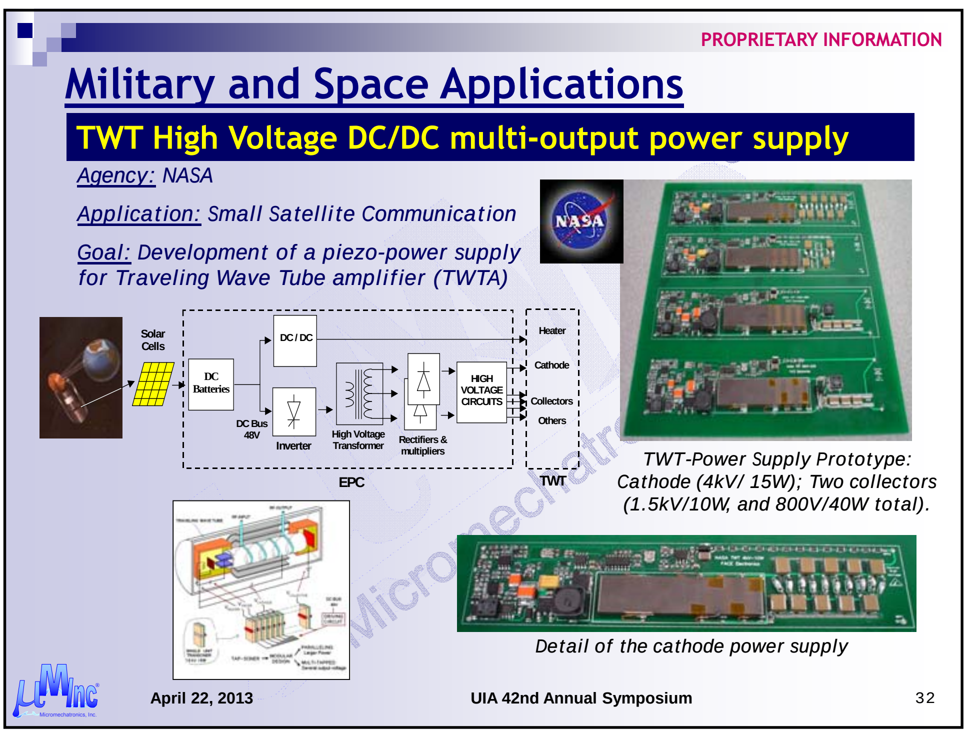
Features

- Miniature, Surface Mount Construction
- Use of Magnetic-less Transformer Technology
- Output Power: 4 W max
- Wide Input Voltage Regulation (8 Vdc to 14 Vdc)
- 0 to 100% Output Programmable
- Output Short Circuit and Over Voltage Protected
- Operating Temperature: -25 ºC to +70 ºC
- Low Ripple: 0.1 % of Vout at full Vout
- High Efficiency > 80 %
- Programming Voltage: 0 to 2 Vdc
- Input and Output Connectors for easy plug and play integration.






PROPRIETARY INFORMATION
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
DARPA
PROPULSION SYSTEMS
THRUSTERS
COMUNICATION PAYLOADS
DETECTORS, SENSORS, ETC
BATTERY BANK
NASA-SBIR Phase II, (2002-4)
NASA-SBIR Phase II, (2003-5)
April 22, 2013
UIA 42nd Annual Symposium
31


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)
Solar Cells
DC Batteries
DC / DC
DC Bus 48V
Inverter
High Voltage Transformer
Rectifiers & multipliers
HIGH VOLTAGE CIRCUITS
Heater
Cathode
Collectors
Others
EPC
TWT
TWT-Power Supply Prototype: Cathode (4kV/ 15W); Two collectors (1.5kV/10W, and 800V/40W total).
Detail of the cathode power supply
April 22, 2013
UIA 42nd Annual Symposium
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PROPRIETARY INFORMATION

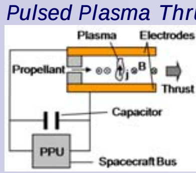
Military and Space Applications

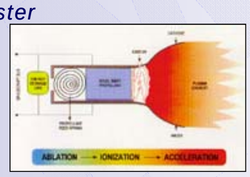
Pulsed Plasma Thurster Discharge Initiation (DI) System

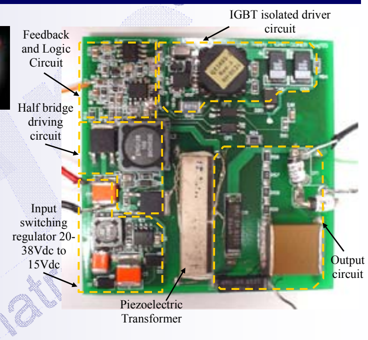
Agency: NASA

Application: Small Satellite Propulsion

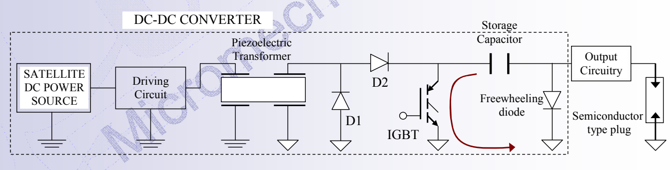
Goal: Integrated high reliability discharge initiation (DI) system for a Pulsed Plasma Thruster







E0-1 micro-satellite using PPT Thrusters

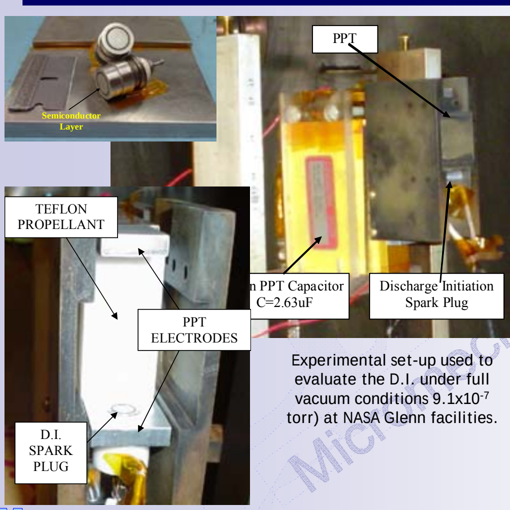


Piezoelectric discharge initiation system using an IGBT solid state switch

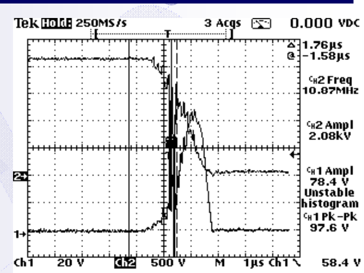
PROPRIETARY INFORMATION

Military and Space Applications

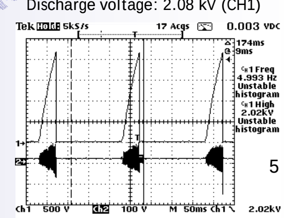
Pulsed Plasma Thruster Discharge Initiation (DI) System



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)



5 Hz

PROPRIETARY INFORMATION

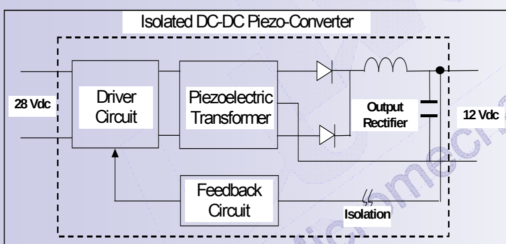
Military and Space Applications

DC/DC Piezo Converter for Satellite Power Bus

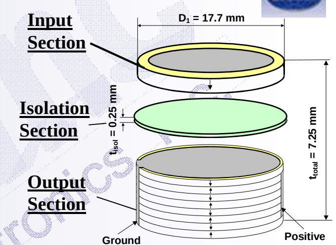
Developed for DARPA under a SBIR contract

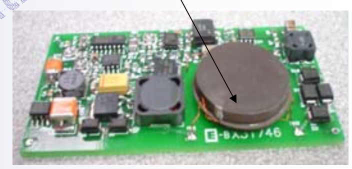
Application: Small Satellite Point of Load converter

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



DC-DC piezo-converter developed by Face



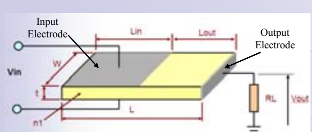


DC/DC 20W Piezo-converter

PROPRIETARY INFORMATION

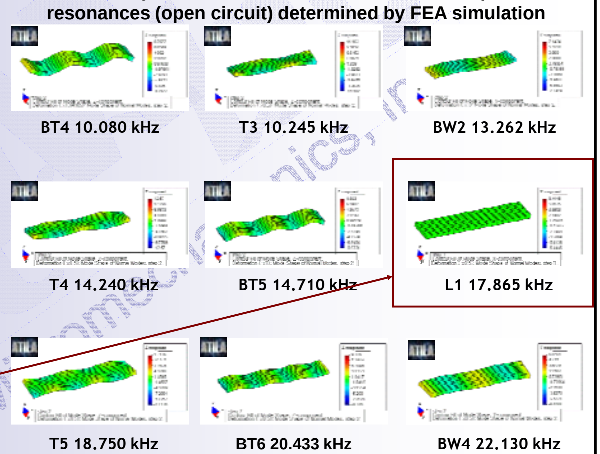
Ultra High Voltage DC-DC Piezo-converters

100kV/20W Piezo Supply for Neutron Source Generator



Single layer design structure and parameters used to optimize the PT

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



PROPRIETARY INFORMATION

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)

ATILA	L x W1 x H			L x W2 x H			L x W3 x H		
	fr	fa	keff	fr	fa	keff	fr	fa	keff
BT4	10.015	10.015	0.88	10.068	10.068	1.24	10.100	10.100	0.87
T3	12.853	12.853	0.00	10.241	10.241	0.00	8.602	8.602	0.00
BW2	10.842	10.842	0.00	13.083	13.083	0.00	14.750	14.750	0.00
T4	17.349	17.775	0.72	14.236	14.236	0.00	12.175	12.175	0.00
BT5	14.638	14.638	15.94	14.705	14.706	0.72	14.700	14.700	0.00
L1	17.349	17.574	15.00	17.345	17.766	21.65	17.339	17.754	21.50
T5	22.625	22.625	0.00	18.735	18.735	0.00	16.390	16.390	0.00
BT6	20.331	20.333	1.51	20.398	20.400	1.50	19.726	19.727	1.08
BW3	18.833	18.833	0.00	21.846	21.846	0.00	23.860	23.860	0.00

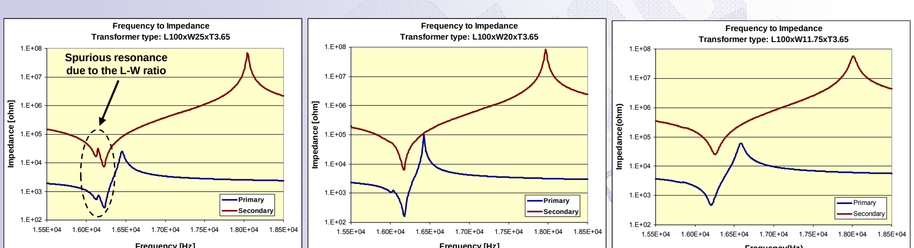
The stronger vibration mode to allow energy conversion is the longitudinal mode, L1. When the width size is W1, the Bending Transversal BT5 mode is very close from the longitudinal, thus decreasing its coupling coefficient. By modifying the width size to W2 and W3, it is possible to separate the BT5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

PROPRIETARY INFORMATION

Ultra High Voltage DC-DC Piezo-converters

100kV/20W Piezo Supply for Neutron Source Generator

6kV/20W High Voltage Single Layer Piezo Transformers - Testing

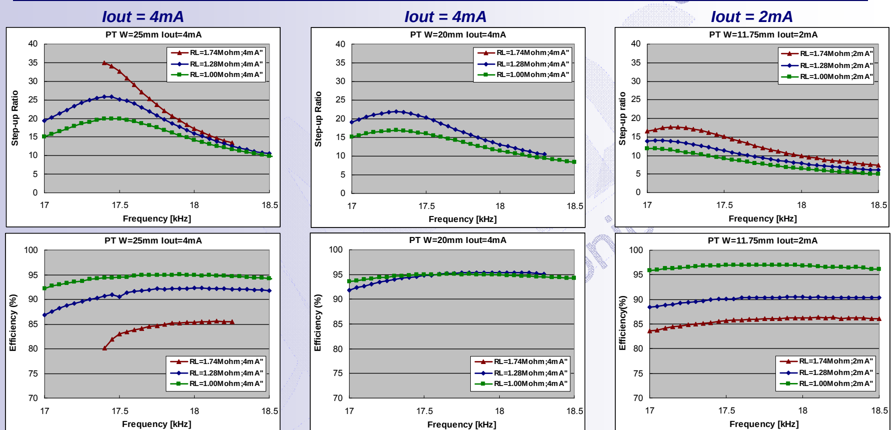


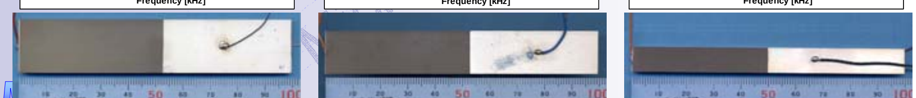
Single Layer PTs prototypes

PROPRIETARY INFORMATION

Ultra High Voltage DC-DC Piezo-converters

100kV/20W Piezo Supply for Neutron Source Generator





PROPRIETARY INFORMATION

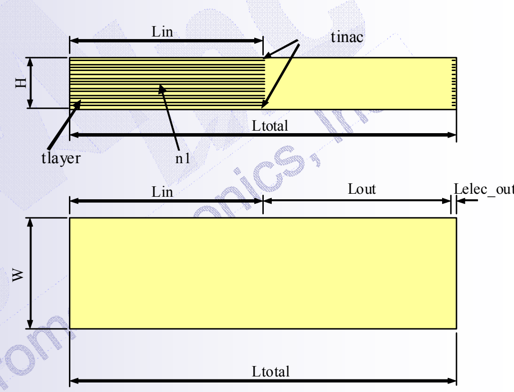
Ultra High Voltage DC-DC Piezo-converters

100kV/20W Piezo Supply for Neutron Source Generator

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

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

PROPRIETARY INFORMATION

Ultra High Voltage DC-DC Piezo-converters

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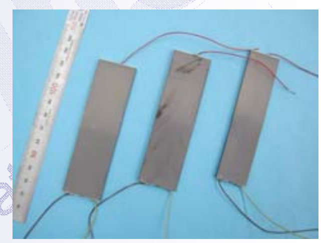
6kV/20W High Voltage Multi-Layer Piezo Transformers

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.



MULTILAYER Piezoelectric transformers successfully sintered

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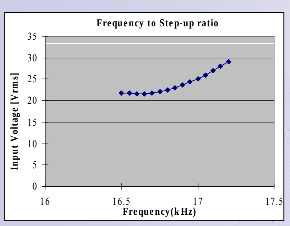
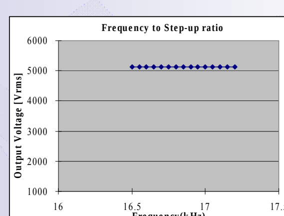
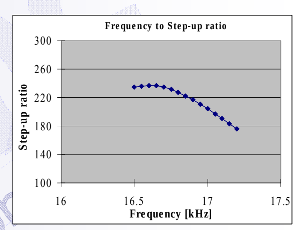
Ultra High Voltage DC-DC Piezo-converters

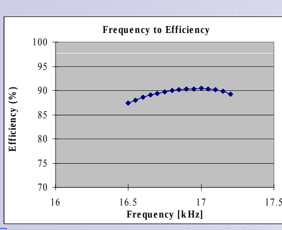
100kV/20W Piezo Supply for Neutron Source Generator

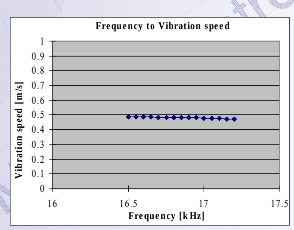
Characterization Multilayer PTs Sample: P=20W / Vout=5kV

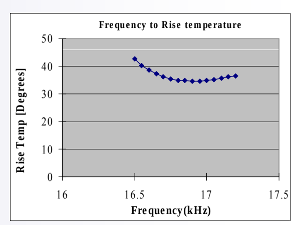












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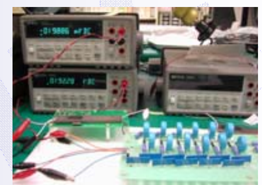
Ultra High Voltage DC-DC Piezo-converters

100kV/20W Piezo Supply for Neutron Source Generator

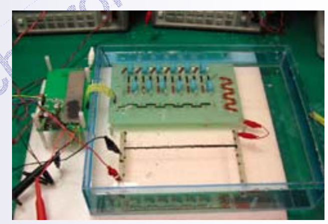
Construction and Testing of the DC-DC Converter

Output multiplier circuit



Testing the PT with the output circuit

DC-DC Converter before encapsulation



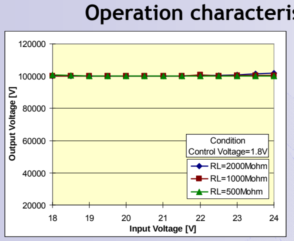
Test in dielectric oil bath under different load

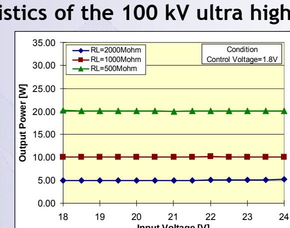
PROPRIETARY INFORMATION

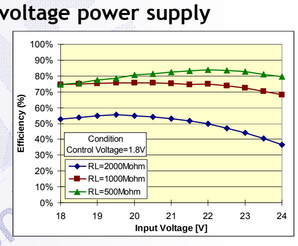
Ultra High Voltage DC-DC Piezo-converters

100kV/20W Piezo Supply for Neutron Source Generator

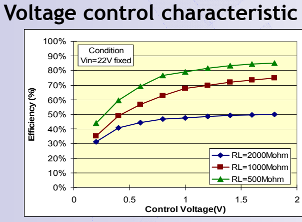
Operation characteristics of the 100 kV ultra high voltage power supply

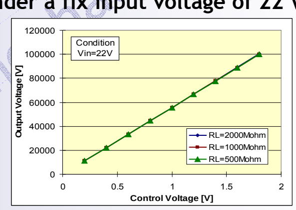






Voltage control characteristic under a fix input voltage of 22 V





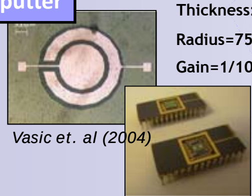
PROPRIETARY INFORMATION

Piezoelectric Transformers: Trends

"Small PTs" - Sub 0.5-mm^3 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.

Sputter



Vasic et. al (2004)

Frequency=45.4 kHz, 185 kHz

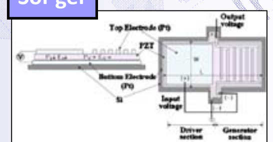
Thickness: Silicon(6um), PZT(4um)

Radius=750um

Gain=1/10 at 45.4 kHz

0.25uW under 5V

Sol-gel



Kim et. al (2006)

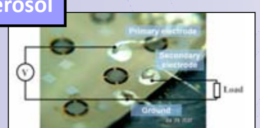
1000x400x5.8 um^3

PZT = 0.4um

IDT Output

Gain = 2.1
at 8 kHz with 1MΩ

Aerosol

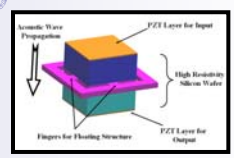


Wang et. al (2007)

Radius=750um

Thickness:
Silicon(8um); PZT(8um)

Gain= 0.58 at 95.5 kHz



Micromechatronics, 2009

Floating Structure

Operation in contour mode

Higher Efficiency