Study of Effect on Resonance Frequency of Piezoelectric Unimorph Cantilever for Energy Harvesting

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Overview

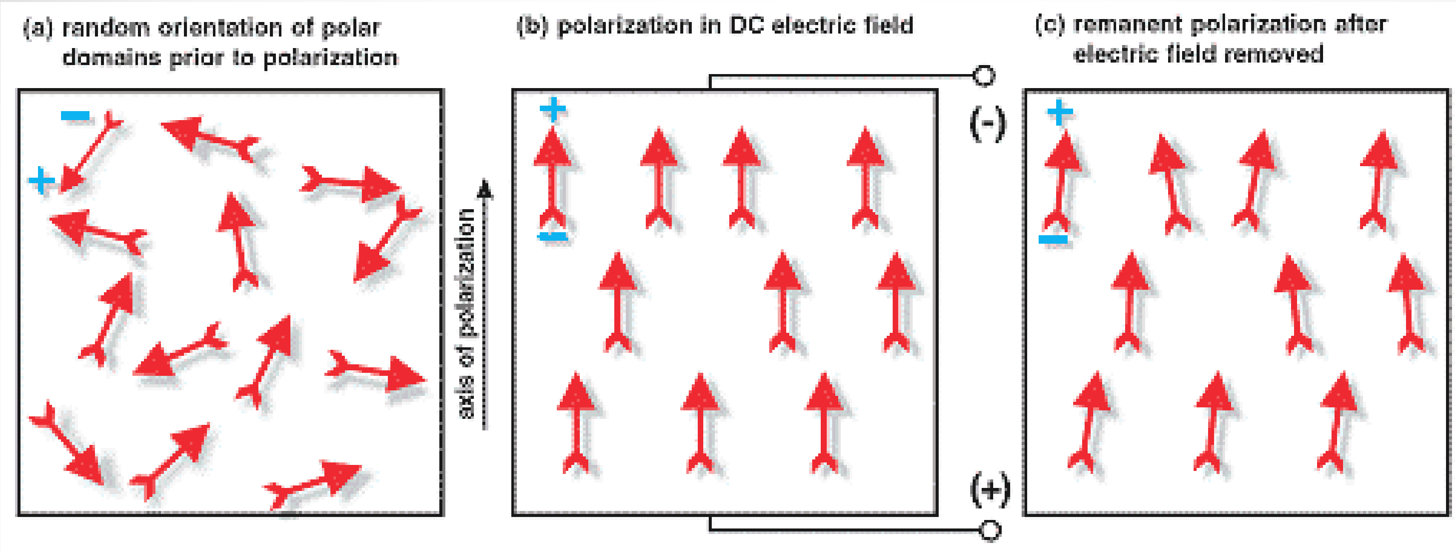
- Introduction
- Piezoelectric Effect
- Piezoelectric Cantilever
- Theoretical analysis using Matlab Simulink
- Modeling using COMSOL
- Conclusion
- References

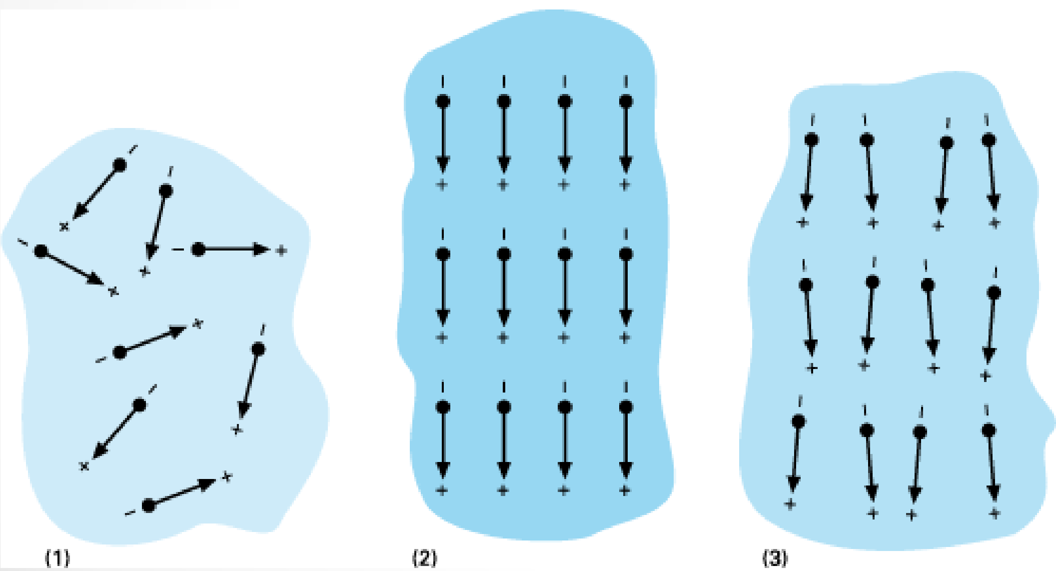
Introduction

- At an average existing mobile Li Batteries has shelf life of 3-4 days.
- To investigate renewable power “scavenging” technologies.
- Piezoelectric materials can provide a direct transduction mechanism to convert signals from mechanical to electrical domains and vice versa.
- Piezoelectric materials are high energy density materials that are suitable for miniaturization. Therefore, this has led to a growing interest in piezoelectric thin films for MEMS applications.

Piezoelectric Effect

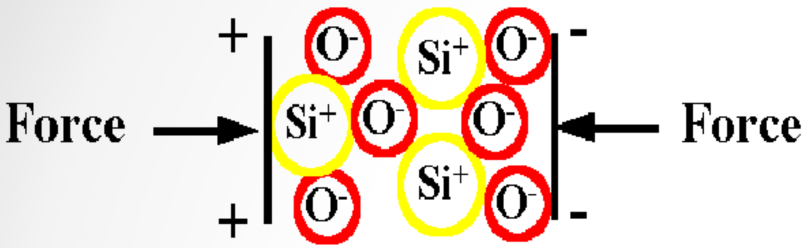
- Appearance of an electric potential across certain faces of a crystal when it is subjected to mechanical pressure
- The word originates from the greek word “piezein”, which means “to press”
- Discovered in 1880 by Pierre Curie in quartz crystals.
- Conversely, when an electric field is applied to one of the faces of the crystal it undergoes mechanical distortion.
- Examples --- Quartz, Barium titanate, tourmaline

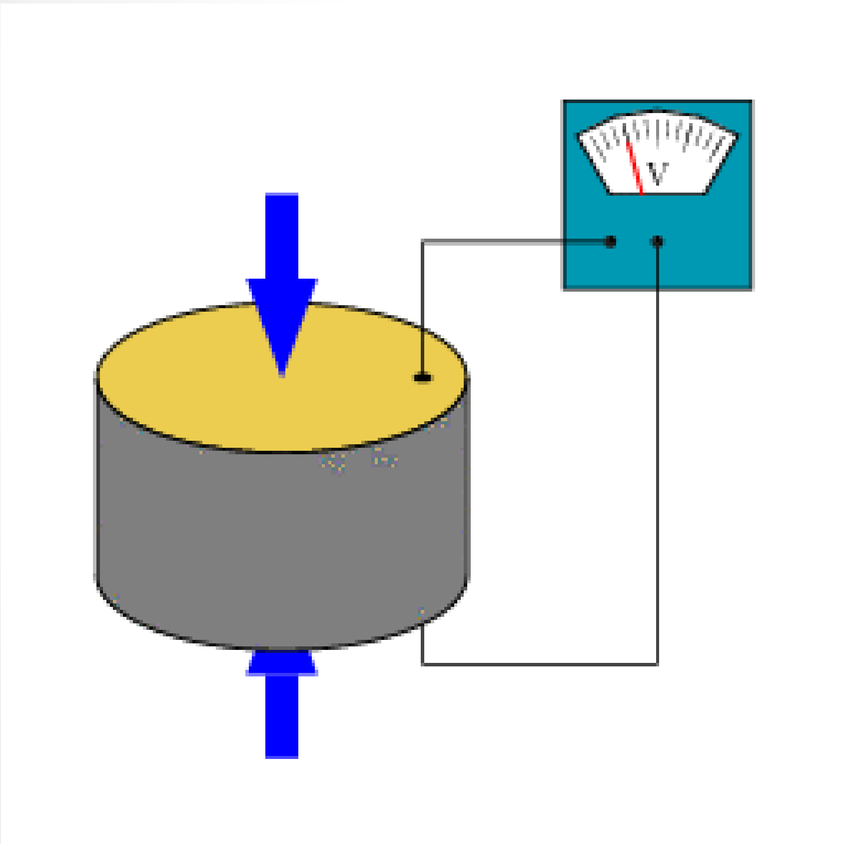




Electric dipoles in Weiss domains; (1) unpoled ferroelectric ceramic, (2) during and (3) after poling (piezoelectric ceramic)

Piezoelectric Effect





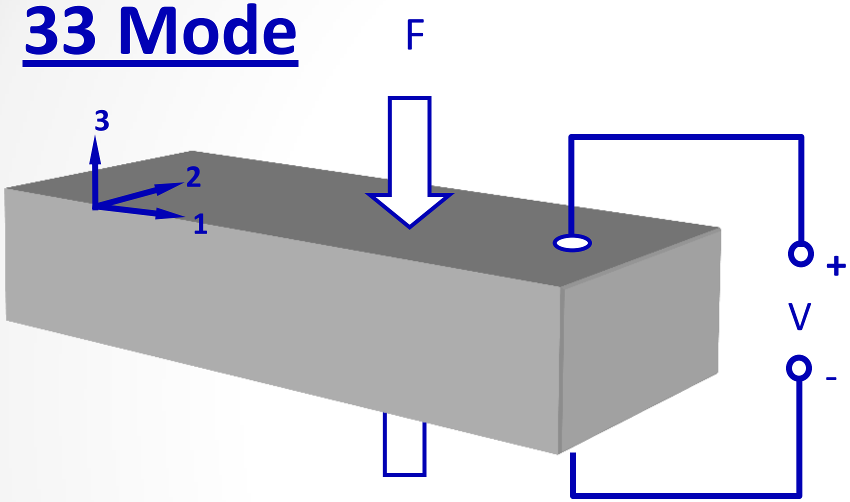
- **displacement of electrical charge due to the deflection of the lattice in a naturally piezoelectric quartz crystal**
- **The larger circles represent silicon atoms, while the smaller ones represent oxygen.**

Why Piezoelectric in MEMS

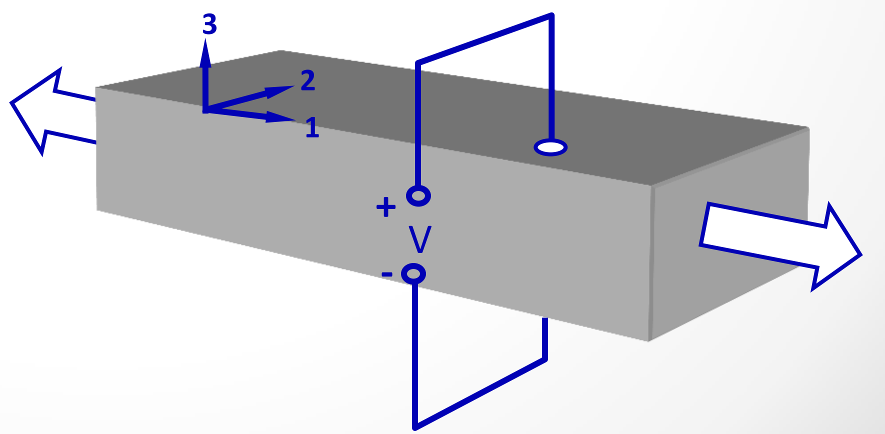
- Suitable for vibrational energy Harvesting
- Compatible with Microfabrication
- Voltages of 2-10V are obtained
- High energy density
- No separate external energy source needed
- Low maintenance
- Good efficiency

Piezoelectric Conversion

33 Mode



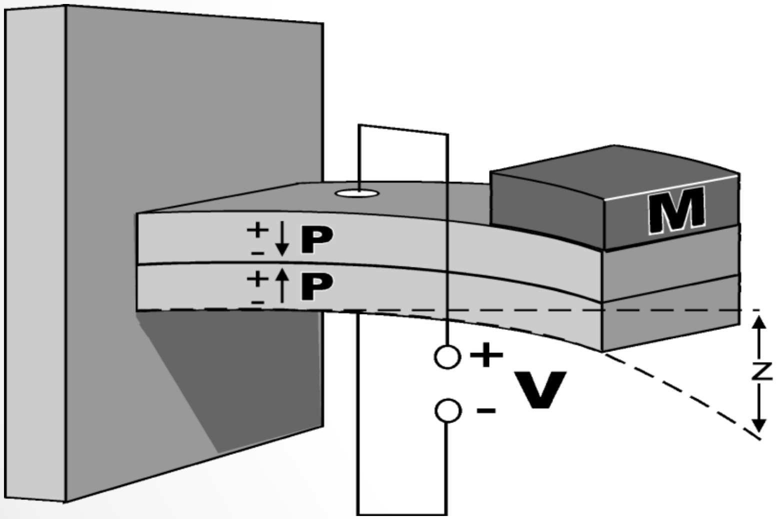
31 Mode

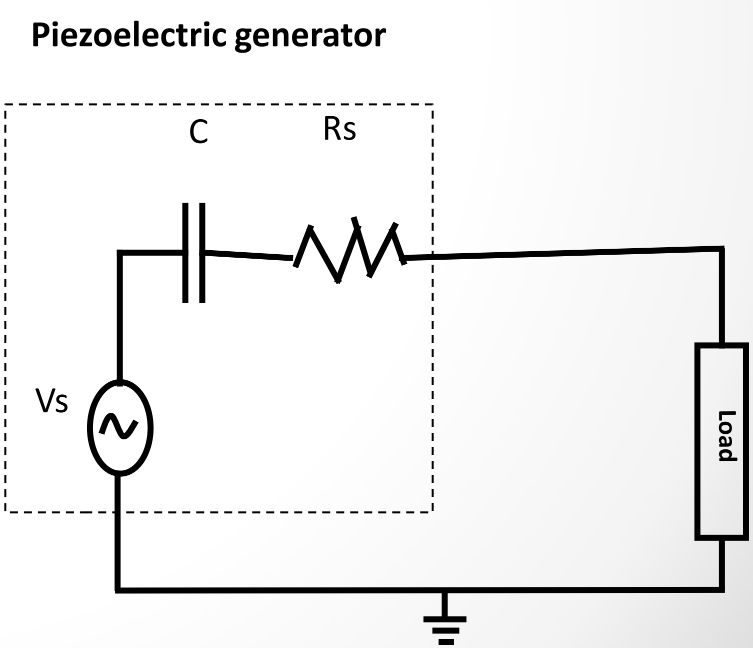


Piezoelectric Cantilever

Piezoelectric

Strain in piezoelectric material causes a charge separation





Design and Modeling Considerations

- Good quality material
- Low resistance
- Thermal management
- Higher power and frequency of operation

Theoretical Analysis

Piezoelectric Unimorph Cantilevers

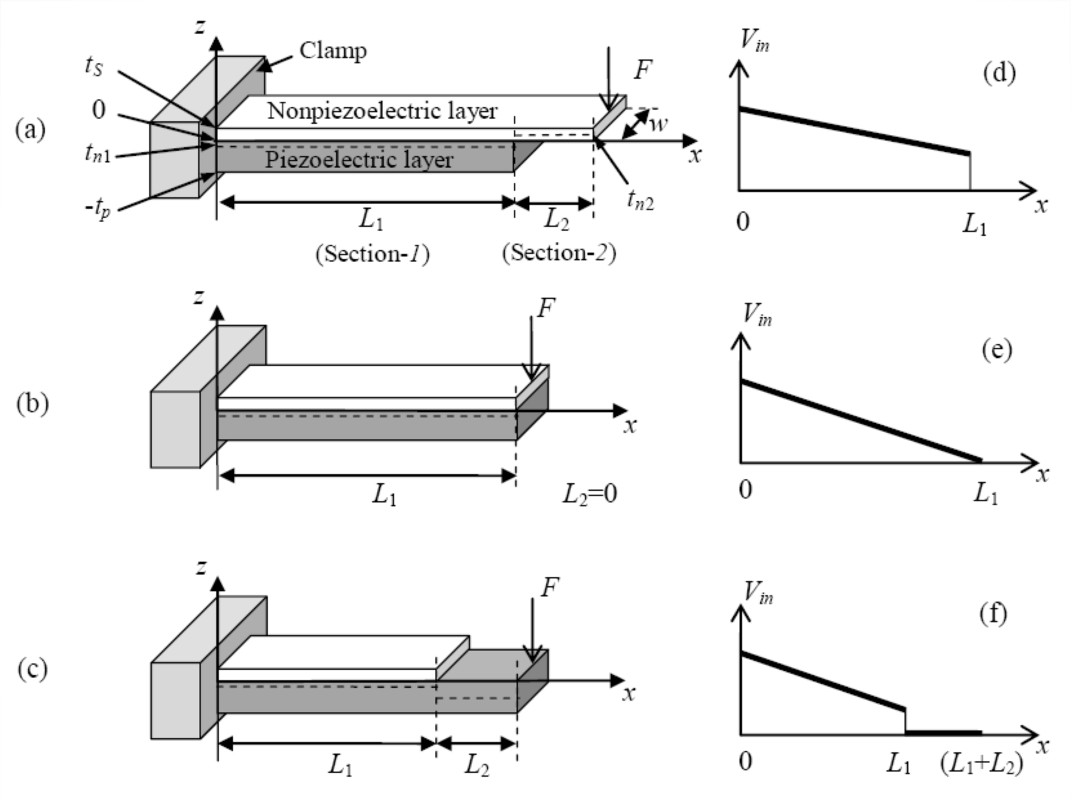
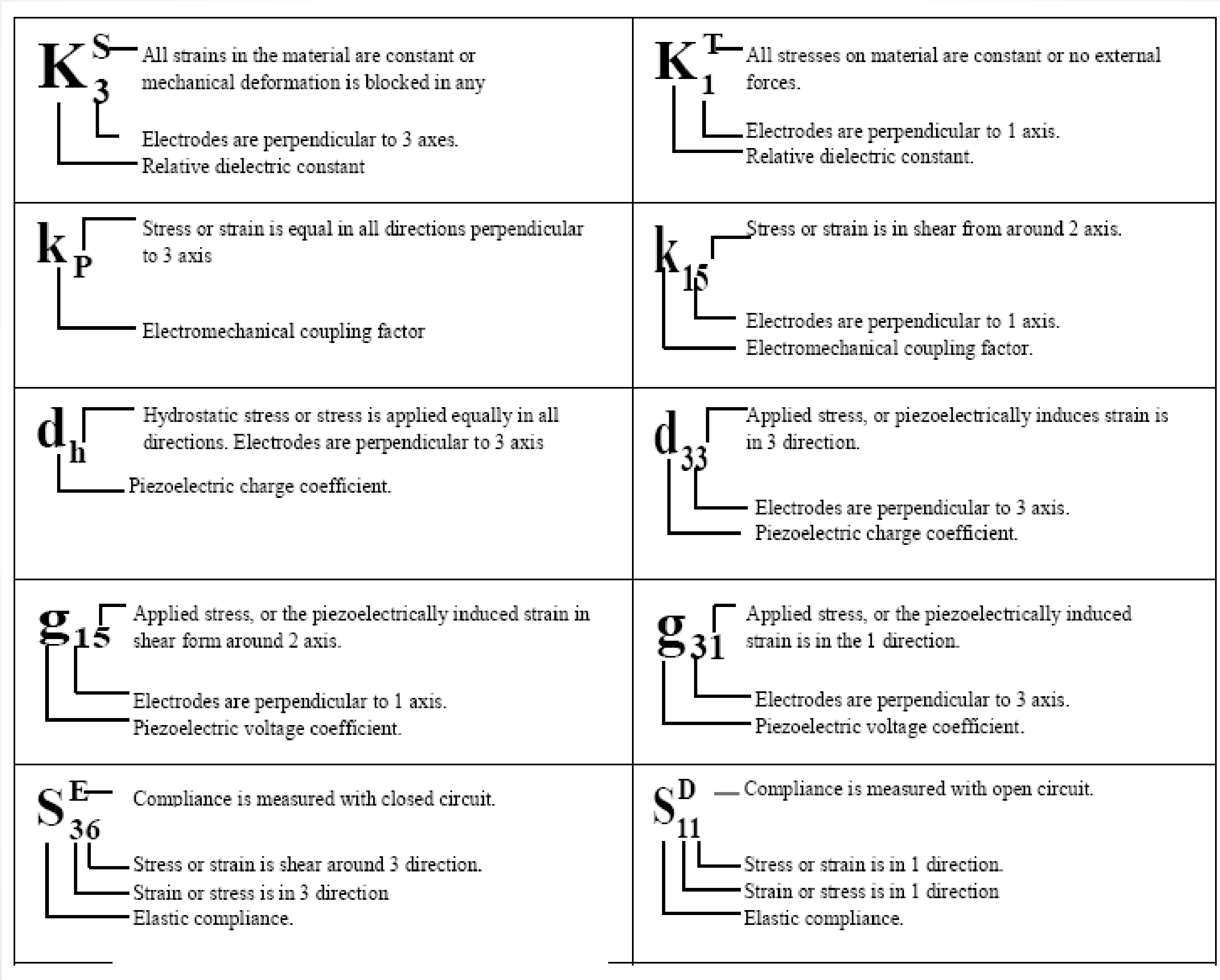


Figure :The schematic of a PUC with the NPL/PL length ratio (a) >1, (b) =1and (c) <1, and the corresponding induced voltage distribution ((d), (e) and (f)) in the piezoelectric layer with a concentrated force, *F*, applied at the tip. Note that in (a)-(c), the dashed lines in Section-*1* and Section-*2* indicate the positions of the strain neutral plane.

Piezoelectric materials are characterized by several coefficients:



Resonant frequency (f_r)

$$f_r = \frac{\omega}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{K}{m_e}} \tag{10}$$

Expressed in terms of Bending modulus per unit width Dp

$$f_n = \frac{v_n^2}{2\pi}\frac{1}{l^2}\sqrt{\frac{D_p}{m}} \tag{11}$$

$$m = \rho_p t_p + \rho_s t_s \tag{12}$$

$$D = \frac{E_p^2 t_p^4 + E_s^2 t_s^4 + 2E_p E_s t_p t_s (2t_p^2 + 2t_s^2 + 3t_p t_s)}{12(E_p t_p + E_s t_s)} \tag{13}$$

The induced voltage unit force $V_{in,ave/F}$ is given by

$$\frac{V_{in.ave}}{F} = \frac{1}{2} L g_{31} \frac{E_p}{w D_1} \left(t_{n1} t_p + \frac{1}{2} t_p^2 \right) \tag{14}$$

$$K = \frac{2wD}{L^3} \tag{15}$$

The induced voltage per tip displacement $V_{in,ave/htip}$ is given by

$$\frac{V_{in.ave}}{h_{tip}} = \frac{3}{4} \frac{g_{31} E_s t_s E_p t_p (t_s + t_p)}{L^2 (E_s t_s + E_p t_p)} \tag{16}$$

Material properties of piezoelectric unimorph cantilever

Table :Material properties of piezoelectric unimorph cantilever

Inputs to the model	ZnO	Pt
Length(µm)	2500	2500
Width(µm)	500	500
thickness(µm)	2	4
Young's modulus[GPa]	123-210	168
Poisson's ratio	--	0.38
Strain Coefficient(10^{-12}m/v)	-5.4 - 11.67	--
Density(Kg/m^3)	3980	21450
Dielctric Constant(ε_r)	9-12.64	--

Simulink Model

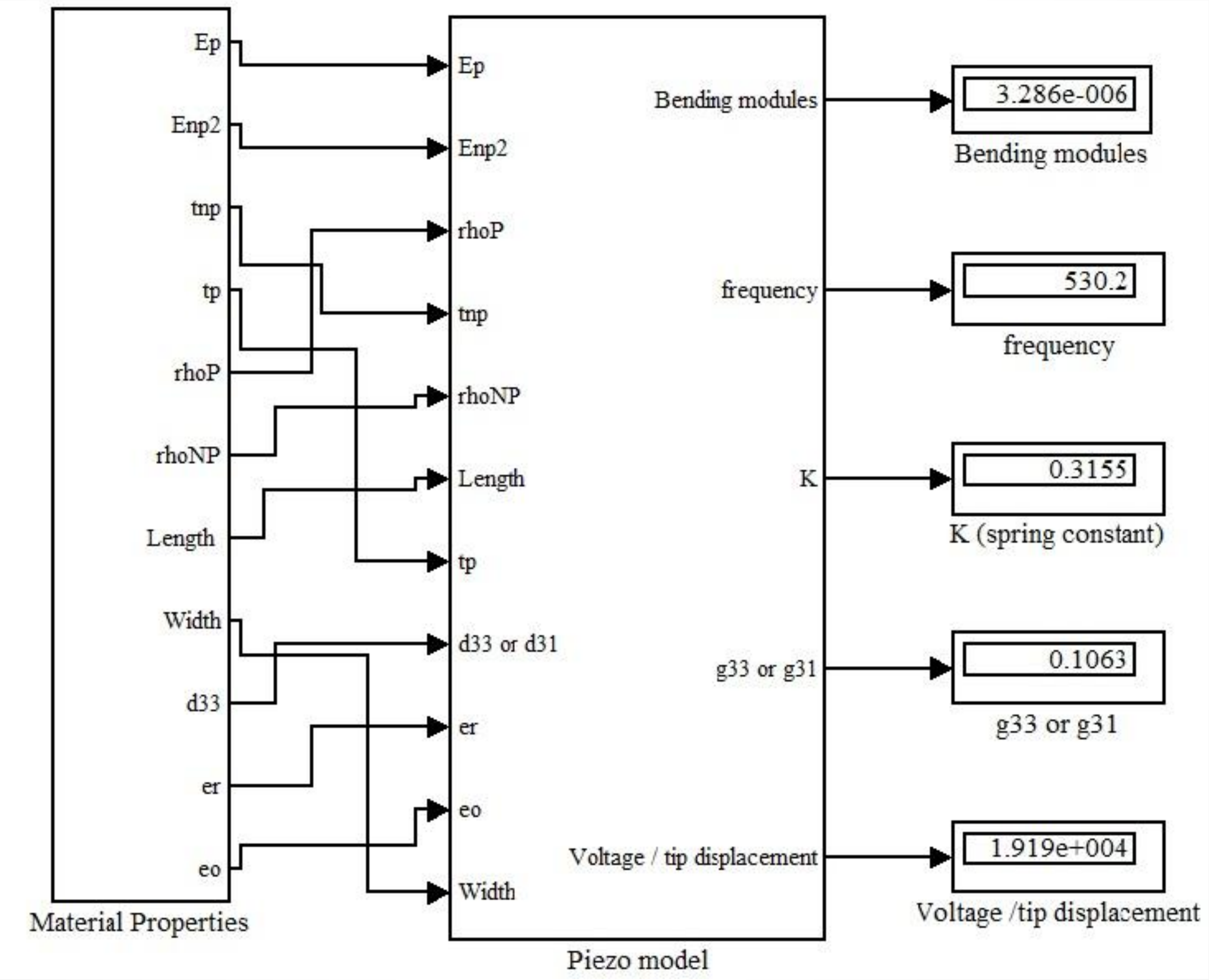


Figure. Simulink model of piezoelectric unimorph cantilever

Simulation using COMSOL Multiphysics

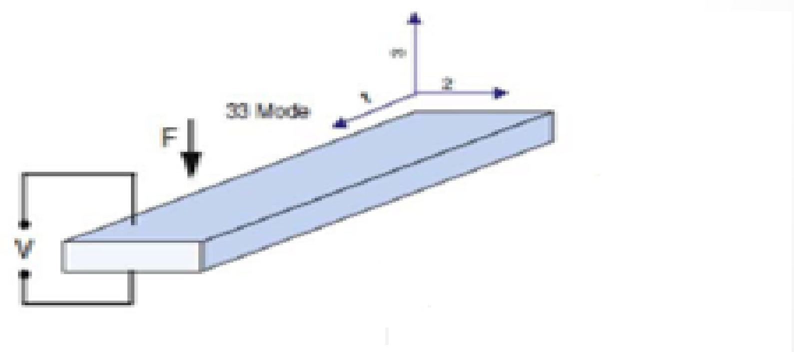
Use of COMSOL Multiphysics

- **Application modes**:

piezoelectric: Mechanical / Electrical behavior

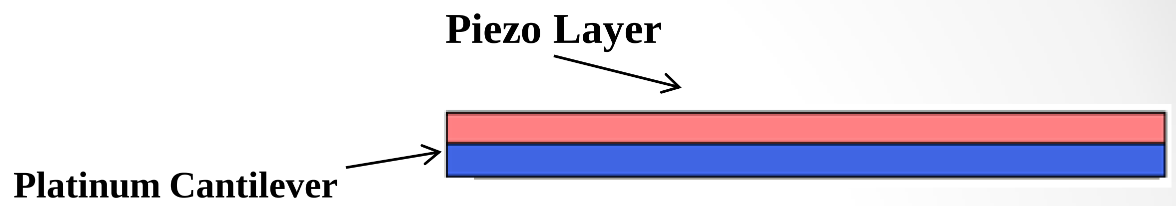
- Generated charge / Electrical potential
- Vertical vibrations application

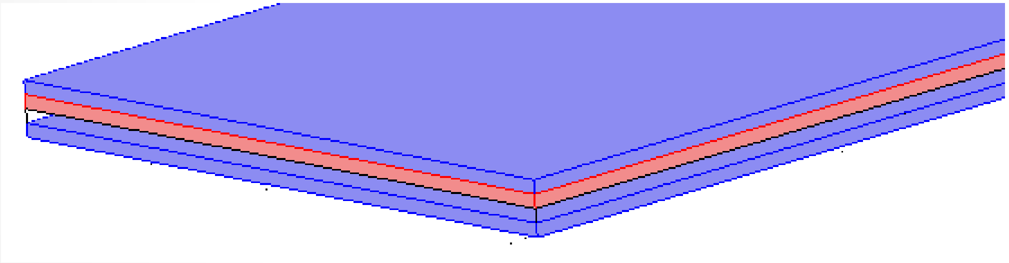
Moving Mesh: Varying Length

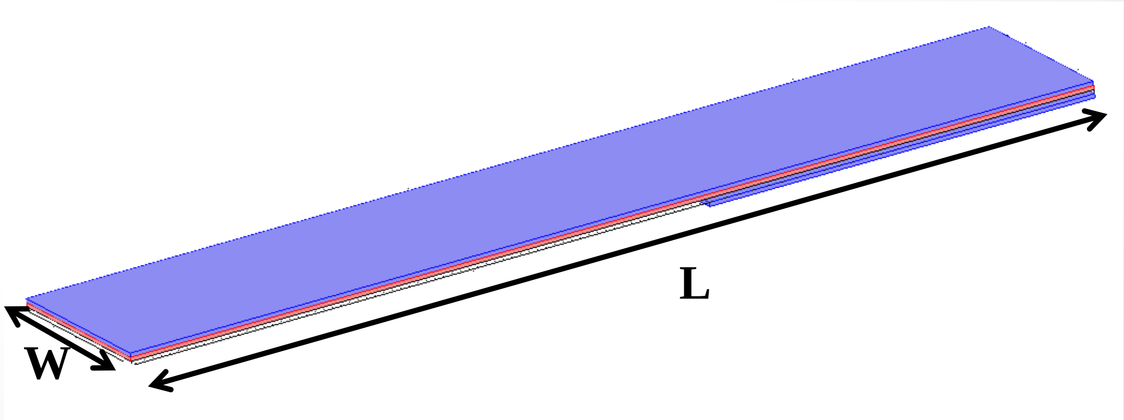


Geometry

- **3D cantilever**
  – lenght L = *2500*µm*;*
  – width w = *500* µm*;*
  – piezoelectric layer thickness t_{ZnO} = 2 µm.
  –Substrate layer t_{sub}=4 µm.

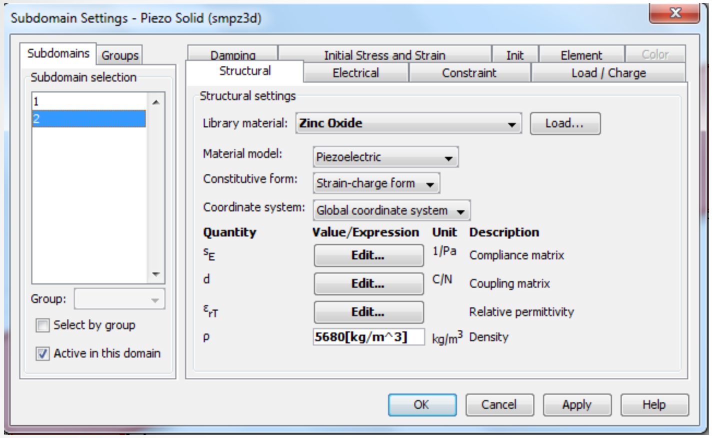


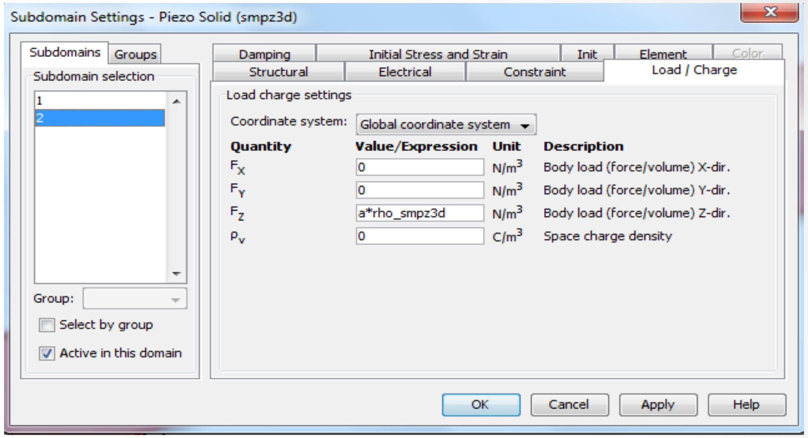




Subdomain and Boundary settings

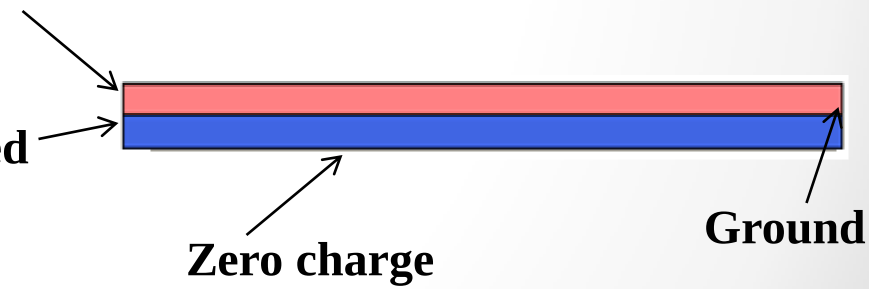
- Subdomain





- Mechanical boundary conditions
  – fixed end

- Electric boundary conditions(piezo layer)
  – Free end: grounded
  – fixed end: floating potential
  – other surfaces: zero charge



Governing equations

- Piezoelectric Equations in strain-charge form

$$S = s^E T + dE$$

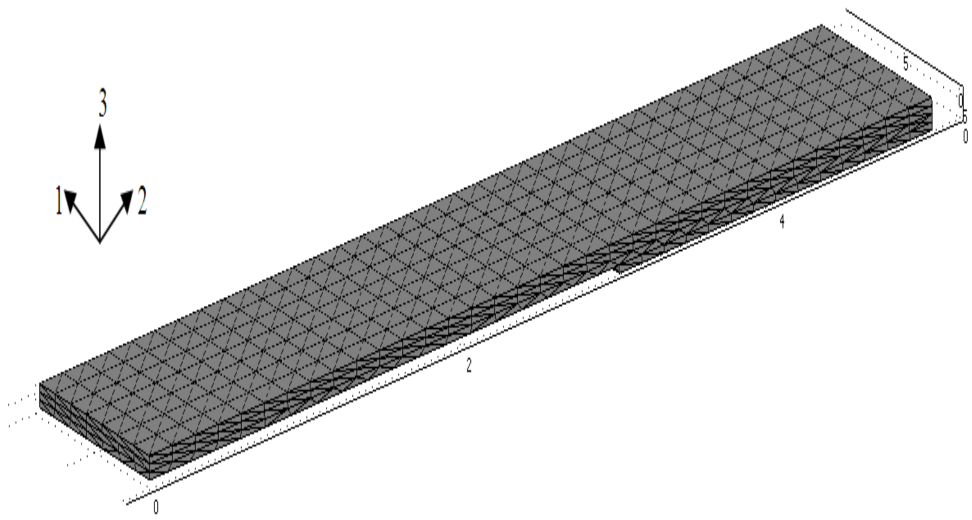
$$D = \varepsilon^T E + dT$$

S = *mechanical strain*
T = *mechanical stress [N/m²]*
s^E = *elastic compliance* [Pa^{-1}]
d = *piezoelectric coefficient [C/N]*
D = *electric displacement* [C/m^2]
E = *electric field [V/m]*
ε^T = dielectric permittivity [F/ m]

$$\rho = 5680 Kg / m^3$$

Meshing

- **Mapped mesh Parameter**



Simulation Results

Eigen Frequency Analysis

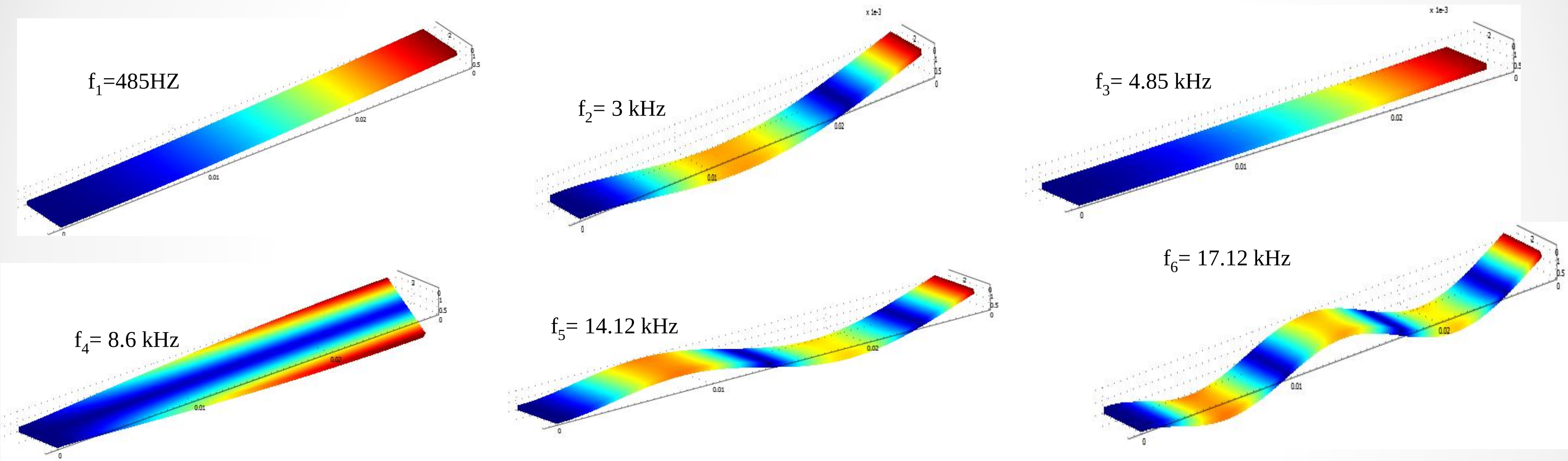
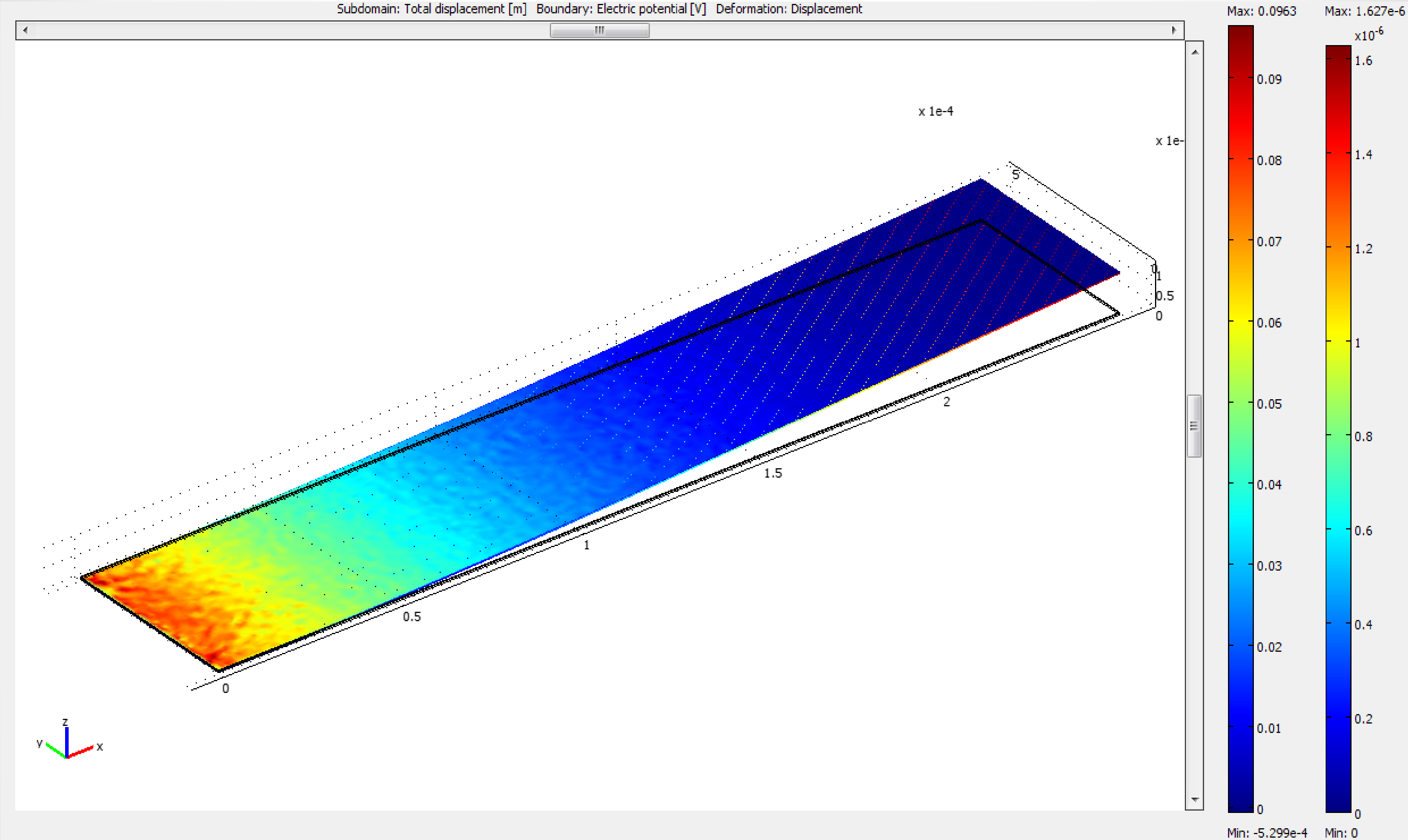


Figure .Model frequency of piezoelectric unimorph cantilever.

Stationary Analysis



Figgure. Tip displacement due to applied Acceleration

Frequency Analysis

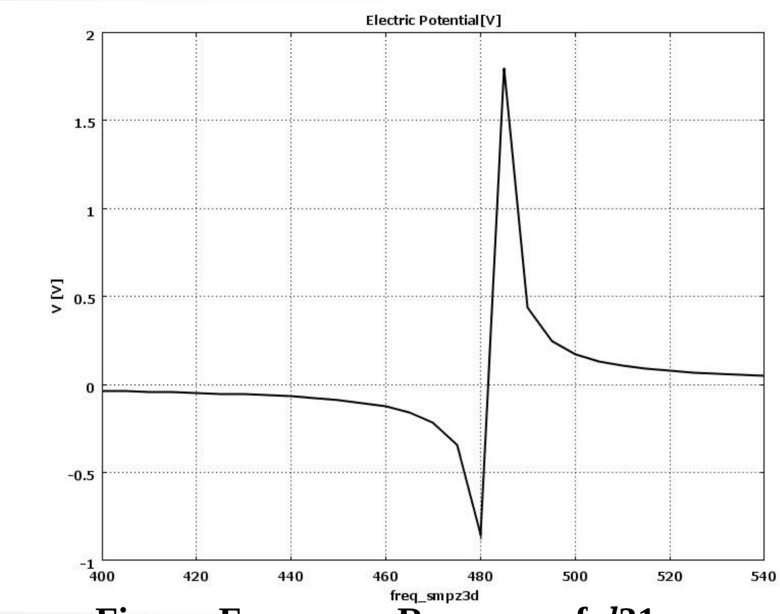


Figure Frequency Response of *d*31

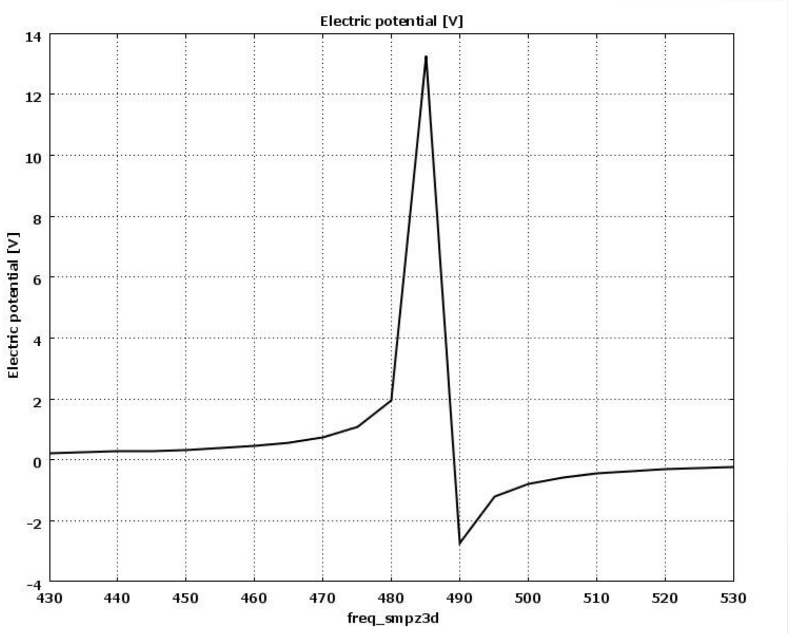
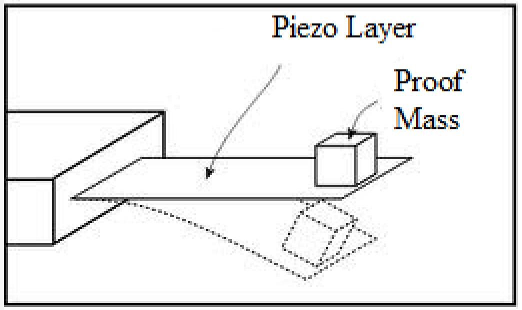


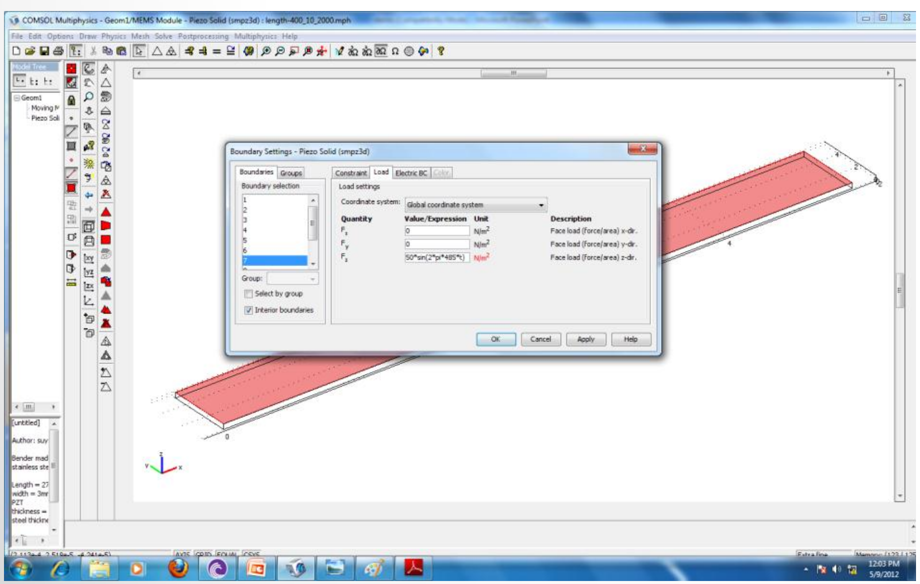
Figure : Frequency Response of *d*33

Time dependent Analysis



➢Harmonic vibration of 50 $N/m2$ amplitude *with* frequency from 450Hz to 510Hz is applied on the top surface of beam, so as to produce vibration. The resonant frequency for both d_{31} *and* d_{33} *structure is 585 Hz*

➢Force per unit area is taken as 50 $N/m2$ which is equivalent to a proof mass of 0.145 mg deposited on tip of cantilever at 9.81m/s^2 acceleration.

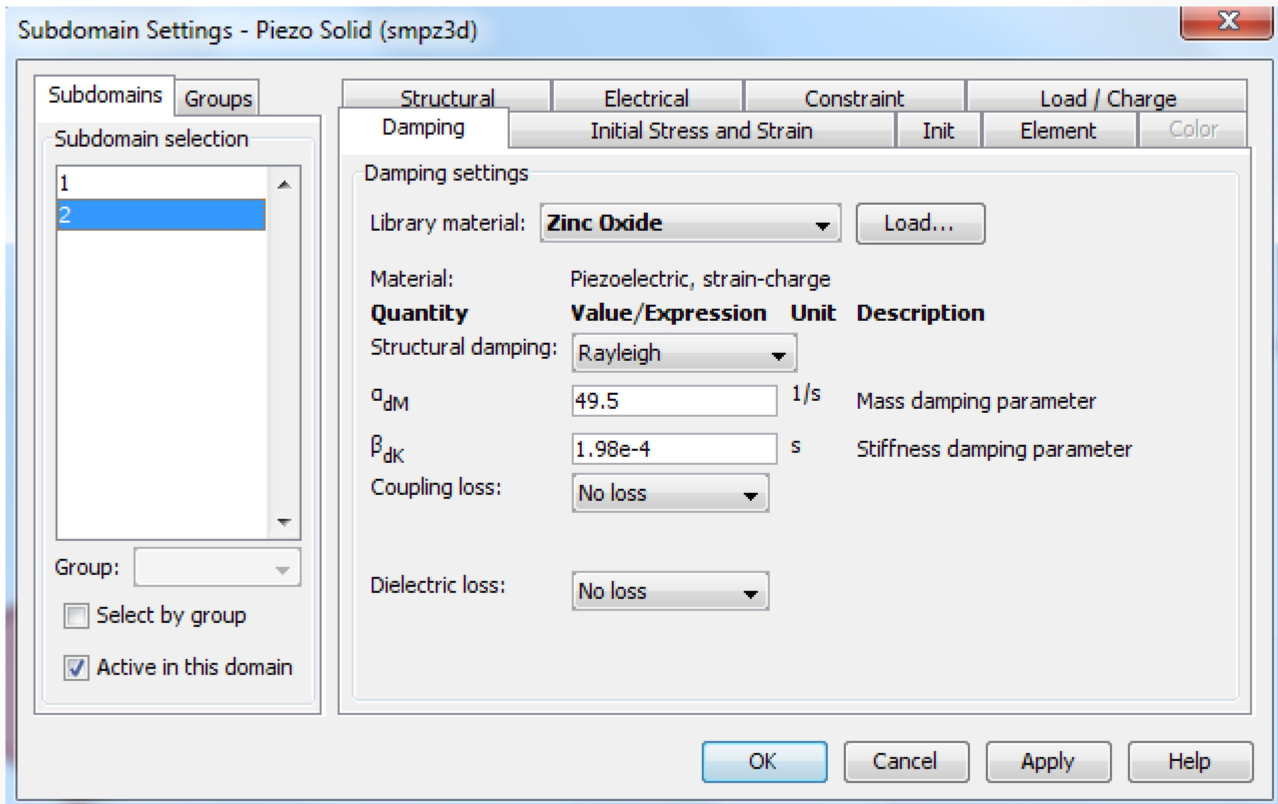


Damping

Rayleigh damping for transient analysis

$$\begin{bmatrix} \frac{1}{2\omega_1} & \frac{\omega_1}{2} \\ \frac{1}{2\omega_2} & \frac{\omega_2}{2} \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} \zeta_1 \\ \zeta_2 \end{bmatrix} \qquad \zeta_1 = \zeta_2 = 0.1$$

$$\omega_1 = 450$$
$$\omega_2 = 510$$



Output of Transient Analysis

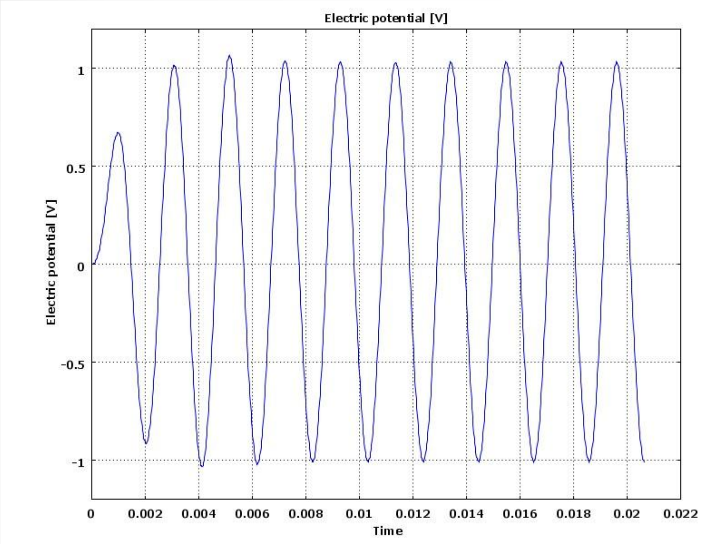


Fig. . Frequency Response of *d*31 mode

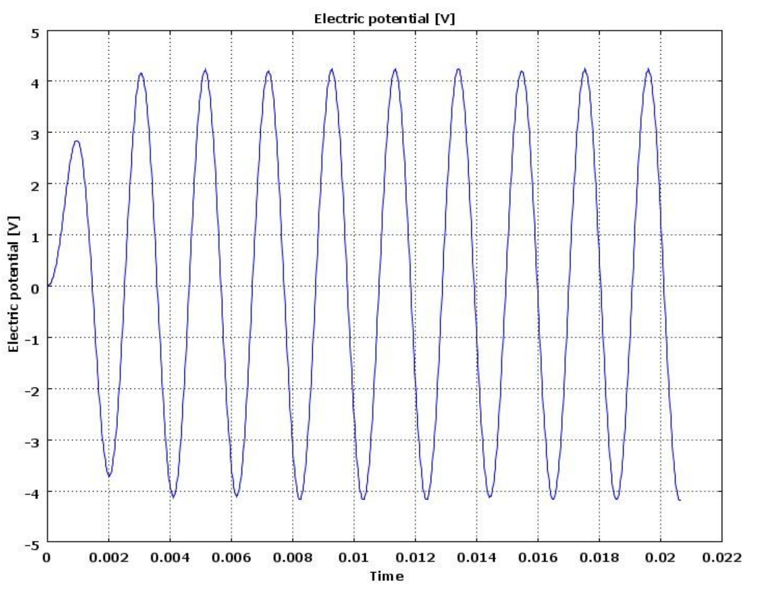


Fig. . Frequency Response of *d*33 mode

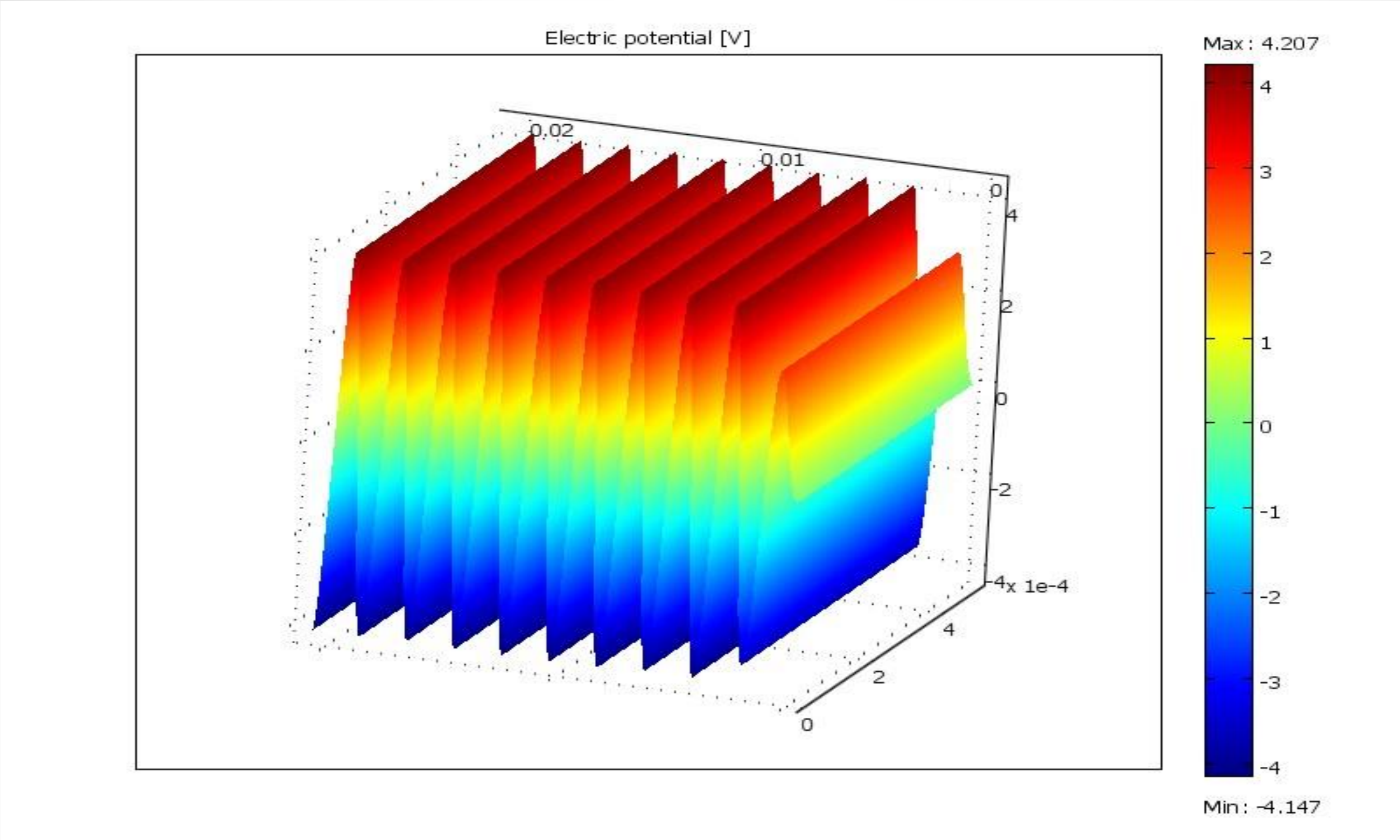


Figure: Extrusion plot showing total displacement of d_{33}

Parametric Segregated Analysis Output

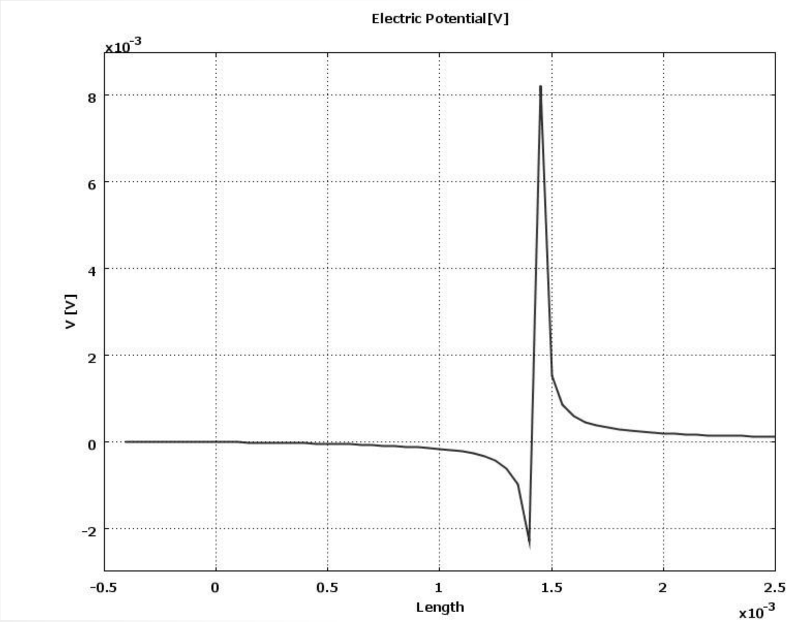


Figure: Plot of total displacement vs length in d31

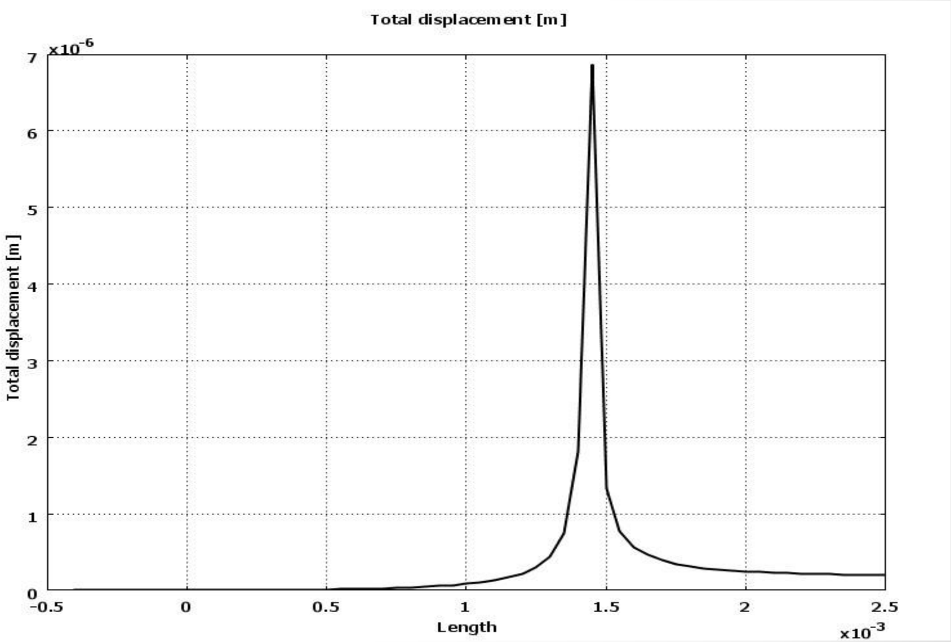


Figure: Plot of total displacement vs length in d33

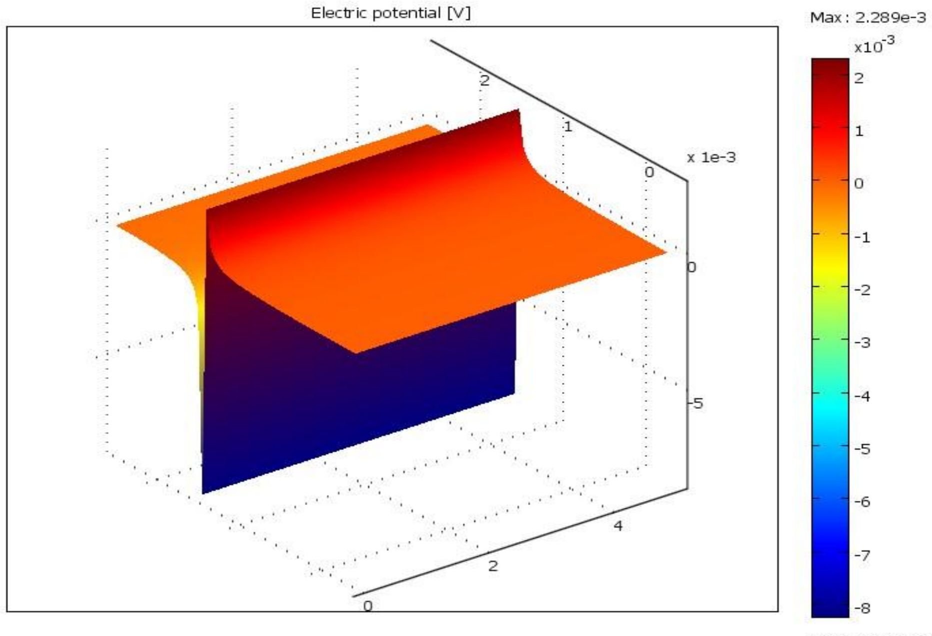


Figure : Extrusion plot for maximum voltage.

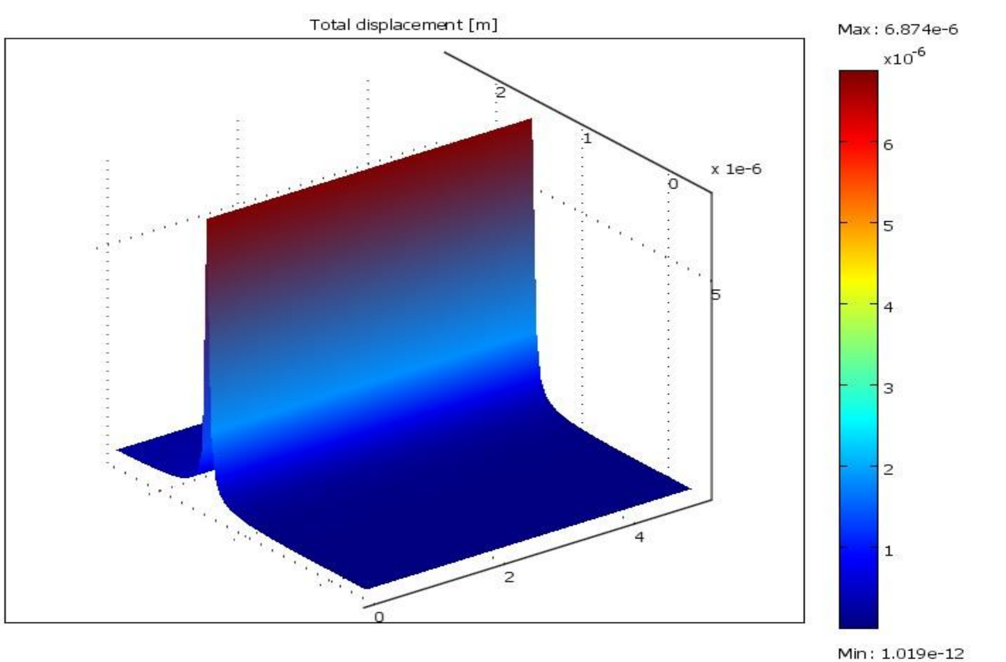


Figure: Extrusion plot for maximum displacement.

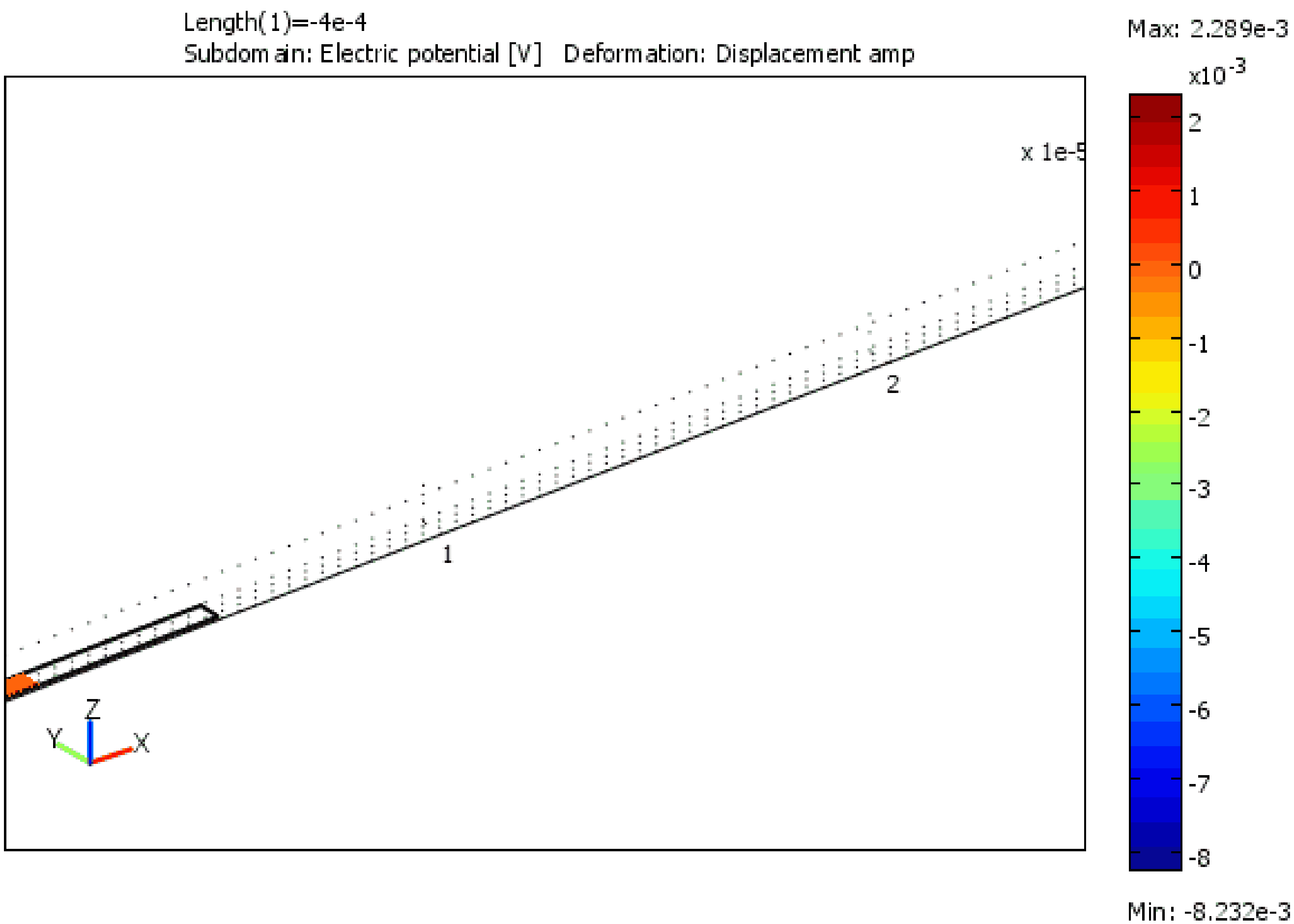

Length(1)=-4e-4
Subdomain: Electric potential [V]   Deformation: Displacement amp
x 1e-5
1
2
Z
Y
X
Max: 2.289e-3
x10^-3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
Min: -8.232e-3

Figure of Merit

Table . Performance Comparison reported MEMS Harvesters

Ref	Device	Dimension	V_{peak}	F(Hz)	Acceleration g	V/mm^3	FOM $V/mm^3.g$
[6]	*d*31 PZT	2mm X 0.6mm X 1.64μm	0.45	608	1	228.7	228.7
[7]	*d*31 PZT	2mmX3.2mmX1.39μm	16	60	0.79	112.4	142.3
[8]	*d*31 ZnO	27mm x .3mm x 0.2mm.	4.7×10^{-9}	10	0.1	2.9×10^{-4}	$.9\times10^{-9}$
[9]	*d*33 PZT	0.8mmX1mmX10μm	2.2	528	0.39	275	705
[10]	*d*33 PZT	0.8mmX1.2mmX2μm	1.6	870	2	833.3	416.6
Proposed	***d*31 ZnO**	**2.5mm x .5mm x 2μm.**	**1.05**	**485**	**1**	**420**	**420**
Proposed	***d*33 ZnO**	**2.5mm x .5mm x 2μm**	**4.2**	**485**	**1**	**1680**	**1680**

Conclusion

- The work presents the study of piezoelectric cantilevers with engineered extensions to effectively convert ambient vibrations into electricity.
- Piezoelectric converters appear to be the most attractive for Micro-scale devices with a maximum demonstrated power density.
- Vibration powered systems are being actively pursued and will be up and running shortly.

Acknowledgement

- NPMASS(National program on micro and smart systems) of Govt of India and IISC Bangalore.

- Suyog N Jagtap for helpful suggestions in carry out this simulation work .

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Thank you.