MODELING OF PZT SLAB FOR GENERATING SYMMETRIC AND UNIFORM AXIAL STRAIN DISTRIBUTION

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Abstract: High frequency modulation of fiber laser is a key requirement for various interferometric fiber optic sensing applications. Piezo ceramic slabs are utilized as modulator for optical fibers or fiber lasers (FLs) with a time varying electric potential. Mounting of FLs on Lead Zirconate Titanate (PZT) slabs are a critical requirement for many fiber optic sensing systems. Careful design of PZT slabs is important for achieving uniform, symmetric & optimum modulation among multiple FLs in such applications. The paper discusses the modelling of PZT slabs with different types of Piezo ceramic materials for optical modulation. COMSOL Multiphysics® software is exploited for modelling & simulation for arriving at optimum design parameters of PZT slab so as to ensure the required modulation. Analysis carried out on the significance of the PZT material composition and its dimensions over the axial strain distribution on the slab. Modelled PZT5H slab with optimum, uniform and symmetrical axial strain for high frequency electric field. Generated uniform axial strain of 160 nano strain (nε) with PZT5H.

Key words: PZT, Fiber Laser, Optical modulation

1. Introduction

Piezo ceramic crystals have broad application from simple strain measurement on cantilever beams, energy harvesting, and up to evolving areas of photonics. PZT ceramic slabs are used for generating frequency modulation on fibers; fiber lasers etc [1] for various applications like interferometric fiber sensing applications [2, 3]. The fiber laser having emission wavelength in C- band, low noise, narrow line width and cavity length of 55 mm is used as laser source in the fiber optic sensing application [1]. The laser is having a frequency noise of less than 25 Hz/√Hz and RIN of less than –120 dB/√Hz at 1 kHz.

With a time varying electric potential, the Piezo ceramic materials generate mechanical strain. The strain generation depends on the electric field, material composition of PZT ceramics and their dimensions [4, 5]. Optical modulation will happen in FLs when they are mounted on the strain region of PZT slabs. The generated optical modulation corresponds to the axial strain on the PZT surfaces. Effective fiber optic sensing demands optimum and symmetric high frequency optical modulation in FLs about 50 kHz frequency [1]. If the sensing system is utilizing multiple FLs, the PZT slab is required to modulate them uniformly [3, 5]. Hence the mounting region of FLs on the PZT surface will be critical. It should be kept as uniform strain region.

The axial strain on the PZT slab is very critical and it is responsible for providing uniform optical modulation. PZT has different resonant modes due to its dimension and geometry. The analysis of resonant states, displacement and the axial strain of the PZT slabs of different material composition and dimensions are discussed in this paper. The present study focuses on the Finite Element Modelling (FEM) of Piezo ceramics slab for axial strain analysis. The design requirement is to generate a symmetric and uniform axial strain by applying electric potential of lesser amplitude. The modelling is done using COMSOL Multiphysics® software version 5.3 and it is utilized to evaluate the performance of the PZT structure with different material compositions and different applied voltages. For analysis, frequency domain is selected in study module. The frequency sweep is set between minimum and maximum frequency range (100 Hz-100 kHz) up to which the analysis has to be carried out. The FEM software simulates the displacement and axial strain response of the PZTs for different frequencies. Ultimate aim of the modelling is to simulate and attaining non-resonant operating frequencies around the 50 kHz region by varying the dimensions of the slabs. While operating at these frequencies, one can ensure uniform frequency modulation for multiple FLs.

2. Modelling and Simulation

Piezo ceramic crystals are used as modulator for optical fibers or fiber lasers. And these modulators should operate at time varying electric field in order to modulate optical signal for the required condition. For this purpose, the operating frequency regions should be free from resonance states. Resonance and anti-resonances will create instability in modulation. Another important constraint affecting the stability of PZT based fiber optic modulator is its axial strain. Strain should be uniform, symmetric and optimum at the required region on the PZT surface for mounting the FLs for modulation purpose. Realising axial strain generation without resonance at the operating frequency is the real challenge in this work.

For modulating purpose, the Piezo ceramic should work on indirect mode, which means when a voltage of equal magnitude is applied to the perpendicular faces of the crystal, it should produce equal amount of displacement on the faces perpendicular to the electric force applied. Inverse piezo electric displacement governing strain charge equation is given below,

$$\boldsymbol{S = s_E T + d^T E}$$

$$\mathbf{S = d_{31}E}$$

The symbols used in the equation are mentioned in Table 1.

s	Strain vector
S	Compliance Matrix
T	Stress Vector (N/m^2)
d^T	Piezo electric coefficient matrix (charge constant)
E	Electric Field Vector (V/m)

Table 1: Symbols of equation

3. Computational Methods

In this work, COMSOL Multiphysics® is used as a tool to design our structure and extract the interested output parameter which is, strain according to the input electric potential. To run a COMSOL® simulation, certain physics modules need to selected for the particular analysis. Electrostatics interface is selected from the AC/DC module for applying electric potential on the surface of PZT. Solid mechanics and piezoelectric interfaces are selected from the structural mechanics module. In electrostatics module, electric potential and ground are applied using terminal and ground node. Multiphysics module will connect both solid mechanics and electrostatics interfaces with each other for ease of computation. The basic computation equations used in the interfaces are given below.

$$\boldsymbol{-\rho\omega^2 u = \nabla . S + F_V e^{i\phi}}$$

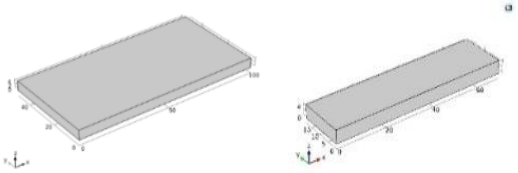
$$\boldsymbol{\nabla . D = \rho_V}$$

$$\boldsymbol{E = \nabla\, V}$$

$$\boldsymbol{D = \varepsilon_0 \varepsilon_{rs} \epsilon + P_{ZE}}$$

3.1 Model Geometry and Meshing

The model chosen in this study is used with the component 3D. Figure 1 is the schematic view of designed models. The dimension of each part of our structure is given by the Table 2. The model is meshed with physics controlled mesh and element size extra coarse. The meshed models are shown in figure 2.

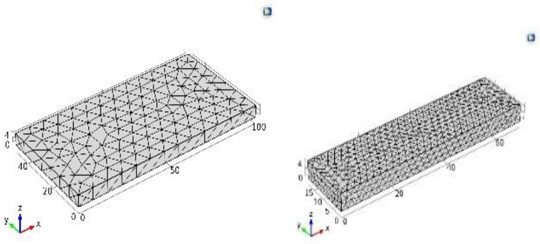


(i) (ii)

Fig 1: Schematic of PZT models (i) PZT8 (ii) PZT5H

Dimensions (mm)	Length	Breadth	Height
PZT 8 Slab	100	50	5
PZT 5H Slab	70	21	5

Table 2: Dimensions of the structure



(i) (ii)

Fig2: Mesh Models (i) PZT8 (ii) PZT5H

3.2 Material parameters

Piezo ceramic materials have different material properties. Primarily, the materials are different in terms of its chemical structure and composition to the pure Piezo electric counterpart. In this modelling Lead Zirconium Titanate (PZT) material is considered for generating axial strain for modulation.

The PZT is a chemical compound of four elements Lead (Pb), Zirconium (Zr), Titanium (Ti) and oxygen (O). The different compositions of these elements results the generation of different PZT materials with various properties. The properties are mainly divided into three; electrical, mechanical and Piezo electric properties. The properties that determine behaviour of Piezo ceramic crystals are relative dielectric constant, Piezo electric charge constant etc. The values are shown in table 3.

PZT8 and PZT5H are selected for modelling and simulation. Since they generate more strain for a particular modulating signal. And modulating signals are directly applied to the PZT ceramic structures. Materials properties for the selected materials are given in the table below.

Material properties	Symbols	PZT 5H	PZT 8
Relative dielectric constant	K_{33}^T	1725	1205
Piezo electric coupling factor	k_p	.6	.5
Charge constant	d_{33}	360	215
	d_{31}	-300	-126
Strain constant	S_{33}	20.7	13.5
Density	ρ	7.6	7.45

Table 3: Material properties

3.3 Electrode boundary conditions

The Terminal node provides a boundary condition for connections with a specified voltage or charge. Terminal node and ground node from electrostatics interface is used for applying electric potential. Specific electric potential can be applied at terminal nodes. Nodes are placed along the two faces of the PZT slabs.

4. Results and Discussions

PZT slabs are modelled with PZT8 and PZT5H materials and the results are discussed below. The requirement is to design a PZT based modulator that can generate sufficient amount of surface strain at high frequency about 50 kHz regions for minimum amplitude of electric field. The strain thus generated should be uniform and symmetrical along the preferred region, where the multiple fiber lasers are mounted for obtaining optimum performance in modulation.

The size and geometry of the modulator is simulated in such a way that the center portion of the cavity of FLs should be mounted comfortably on the modulator surface. Hence the rectangular prism shape modulator is modelled. PZT8 material is simulated first. After that PZT5H material is selected for improving the generated axial strain intensity for electric field of minimum amplitude. At the same time, generation of resonance free states at the required frequency band of 50 kHz region is also a critical requirement. If the resonant states are far away from the required frequency, the generated strain will be much smaller. Then it will not meet the required optimum modulation condition. Hence the resonant state should be at an optimum distance from the required modulating frequency. The dimensions of the PZT slabs are regulated for achieving the optimum position of resonant states for the generation of optimum axial strain value at the particular modulation frequency.

The frequency responses of the modelled slabs are analyzed. The axial strain distributions on the PZT slabs are considered for different modulation frequencies at amplitude of 1 V. The results are compared and scrutinized. The strain distributions at different axes of the slabs are considered. The effort taken for generating required axial strain distribution is discussed. The simulation results and analysis on the PZT8 slab is discussed below.

4.1 PZT 8 Slab

Simulated dimensions of PZT8 slab are 100 mm L x 50 mm W x 5 mm T. The frequency response of the simulated slab is shown in figure 3. The graph is plotted the Admittance values of PZT8 slab for different modulation frequencies at amplitude of 1V.

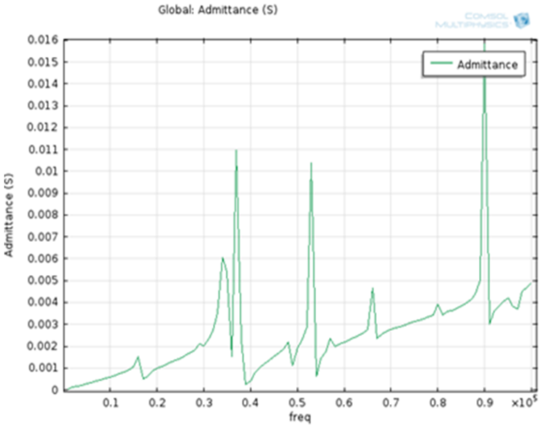


Fig 3: Total Resonance plot of PZT 8 Slab

Total frequency response of PZT 8 slab shows multiple resonant states. At the resonant frequencies the admittance value will be higher. The admittance value indicates the intensity of strain at particular frequency. The required 50 kHz frequency region is crucial, which is free from the resonant states. At the same time, one resonant state of 53 kHz is observed near to desired frequency region. This will support to provide the sufficient amount of axial strain for optical modulation.

Axial strain distributions on the slab are analyzed for different frequencies, such as 45 kHz, 50 kHz and 53 kHz. The axial strain distributions are shown in figure 4, 6 & 8. The strain values are mentioned in figure 5, 7 & 9. The measurement of strain is done along the length of the slabs. The axial strain values along the width of slab at 50 kHz is shown in figure 10.

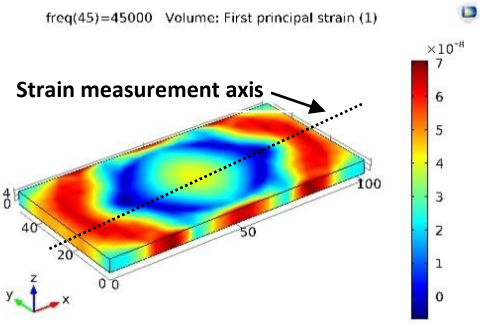


Fig 4: Axial strain distribution @ 45 KHz

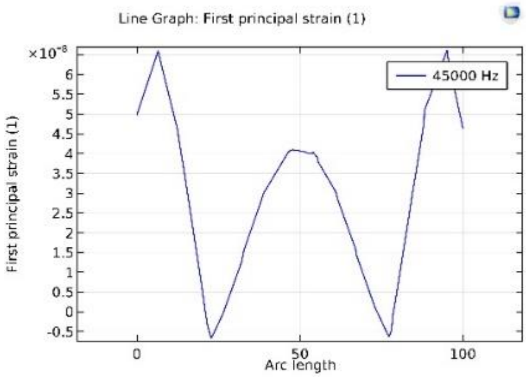


Fig 5: Axial strain plot along length of slab @ 45 KHz

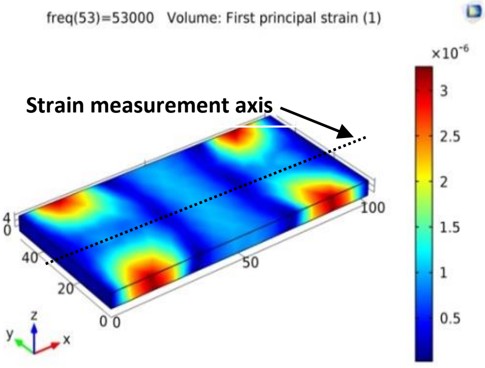


Fig 6: Axial strain distribution @ 53 KHz

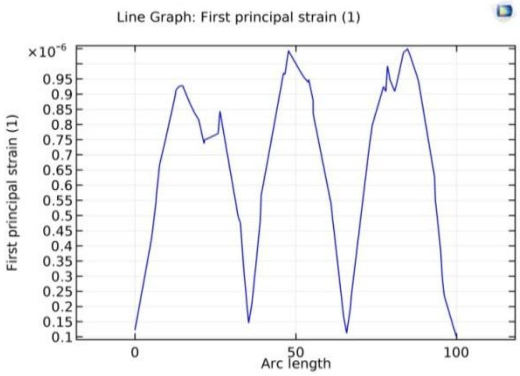


Fig 7: Axial strain plot along length of slab @ 53 KHz

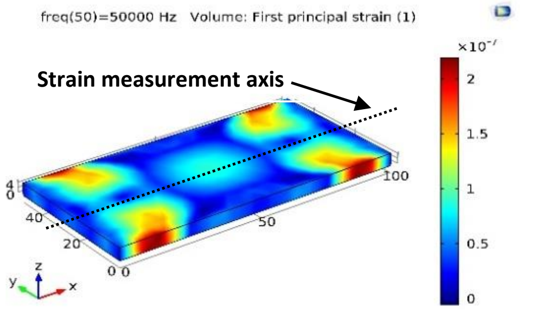


Fig 8: Axial strain distribution @ 50 KHz

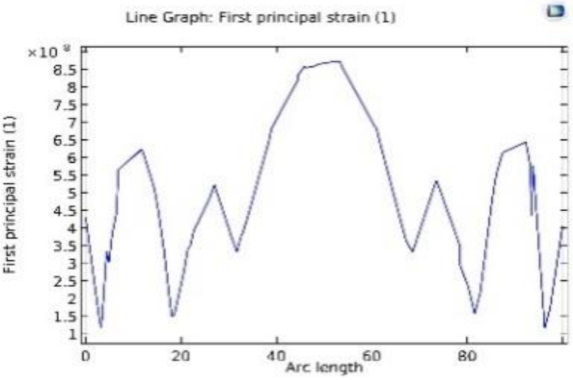


Fig 9: Axial strain plot along length of slab @ 50 KHz

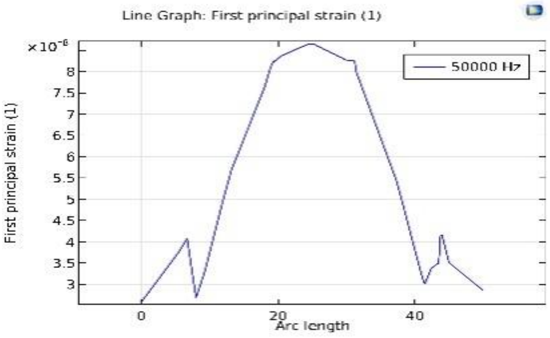


Fig 10: Axial strain plot along width of slab @ 50 KHz

The generated axial strain is approximately 86.8 nε at modulating electric field of amplitude 1 V, which is same as the strain along length axis. The strain generated at the center of slab is mentioned in the Table 4 for different modulation frequencies.

PZT 8		
Frequency (KHz)	**Admittance**	**Strain (nε)**
45	.00152	40.7
50	.00195	86.8
53	.01035	1001.8

Table 4: Comparison of strain values

At the frequency of 45 kHz, the admittance is lesser compared to other frequencies. Hence the axial strain value is also smaller compared to others. At the 53 kHz resonant frequency, the strain is very high corresponding to its large admittance value. But it generates more non-uniform strain at the center of slab. More uniform axial strain is generated at 50 kHz frequency with moderately high value.

The 3 dimensional axial strain distributions at 50 kHz modulation is shown in figure 11. From this figure, it is observed that the center region along the width of the slab having more uniform in strain distribution. The marked region in magenta rectangle is suitable for mounting the multiple numbers of FLs for modulation.

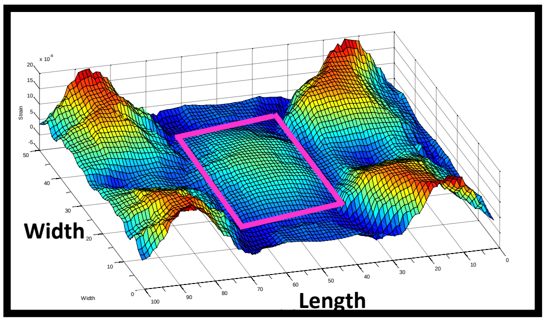


Fig 11: 3 D Axial strain distribution @ 50 KHz

4.2 PZT 5H Slab

Simulated the PZT8 slab and analyzed the axial strain distribution at different modulation frequencies. This slab generates 86 n strain at its center with modulation frequency of 50 kHz at amplitude of 1 V.

Strain on PZT depends on the material properties. By changing the PZT material composition, strain will be improved. PZT5H material is considered, which has high charge constants and strain constants compared with PZT8 material. The dimensions are 70 mm L x 18 mm W x 5 mm T. The frequency response is this slab is shown in figure 12.

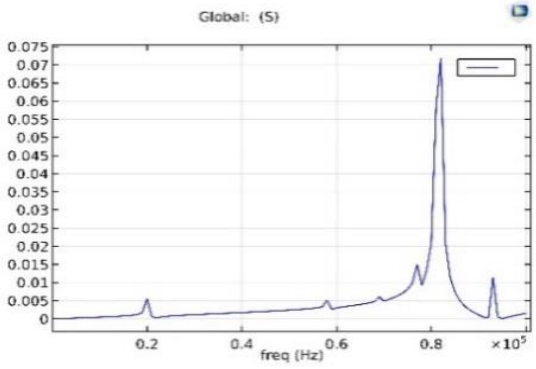


Fig 12: Total Resonance plot of PZT5H Slab

It is observed that, the multiple resonant states in the 50 kHz region is reduced. The admittance value of this slab at 50 kHz modulation frequency is 0.00245, which is higher than previous slab. The axial strain distribution of this simulated slab at 50 kHz modulation along the length is shown in figure 13. The corresponding axial strain plot is shown in figure 14. At the center portion of the slab, the strain is approximately 160 n strain. It is more uniform and symmetric. The center region along the length of slab is appropriate for mounting the multiple numbers of FLs for uniform modulation. The strain on different axes of the slab from the center axis are plotted and shown in figure 15.

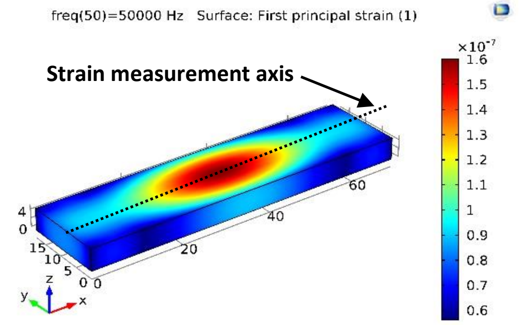


Fig 13: Axial strain distribution @ 50 KHz

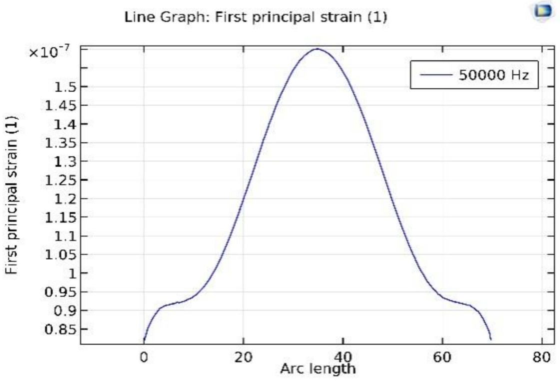


Fig 14: Axial strain plot along length of slab @ 50 KHz

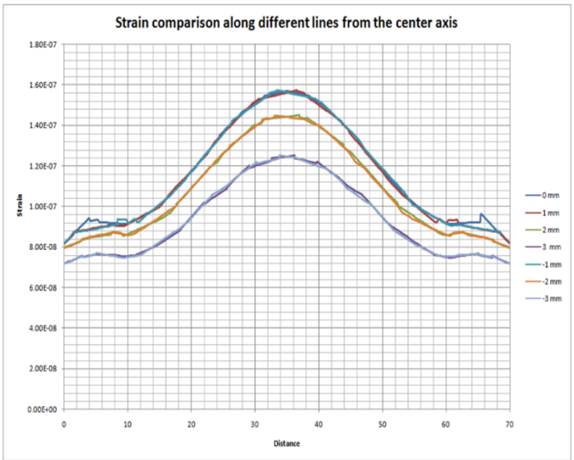


Fig 15: Axial strain comparison at different axes

5. Conclusion

PZT slabs with PZT8 and PZT5H materials for modulating fiber lasers are modelled and simulated. Generated resonant free states at the required frequency region. The significance of PZT material properties and PZT slab dimension on the mechanical strain generation is analysed. Modelled and simulated uniform and symmetric strain region on the PZT slab. A suitable region on the PZT slab for mounting the multiple numbers of FLs for required optical modulation is identified in this work. Analysis is done for the axial strain generation at different axes of PZT slabs. Simulated the axial strain of 160 nε from PZT5H slab at 50 kHz modulation of 1V amplitude, which is 1.8 times higher than the strain of PZT8 slab at same conditions. In this work high axial strain for lesser modulation drive voltage was achieved at non-resonant operating frequencies of the PZT slabs, thereby giving optimum frequency modulation to multiple no of FLs.

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