Optical MEMS Sensor for measurement of Low Stress using Ptolemy II

I. Mala Serene, Rajasekhara Babu M, Zachariah.C.Alex

School of Computing Science and Engineering, VIT University,
School of Electronics Engineering, VIT University,
Vellore-632 014, Tamil Nadu, India

Abstract

Modeling and simulation plays vital role in the Micro Electro Mechanical Systems (MEMS) field. Optical MEMS comprise of three domains namely optical, electrical and mechanical. The existing MEMS software for modeling is very expensive. This cost of modeling software increases the design and development of optical MEMS sensors. This paper proposes the design and development of a novel optical read out mechanism. This mechanism is used to measure the maximum stress applied on the cantilever and its corresponding deflection of the cantilever. The experiments have been carried out using Ptolemy II software for design and simulation of MEMS optical sensors. Laser Actor, a Photo detector and Force Actor have been created using Ptolemy II. COMSOL software has been used to model cantilever. A comparative study has been done for cantilever with three modes of Eigen frequencies using COMSOL. The experimental result shows that the Parylene optical MEMS force sensor can sense less range of stress 0.0003 N/m to 0.272 N/m when compared to the Polyimide optical MEMS sensor.

Keywords Microcantilever, Optical MEMS, Ptolemy, Sensor, Laserdiode, COMSOL

1 Introduction

Optical MEMS can be defined as micro devices with three functionalities like electrical, mechanical and optical at the same time and can be fabricated using batch processing techniques developed from microelectronic fabrication [1]. For integrated micro-systems composed of electrical, optical and mechanical components, the need to model large numbers of linear and non-linear components with sufficient accuracy to analyze cross-talk, noise and tolerance in an interactive environment leads to the requirement of an efficient yet accurate mixed-technology simulation technique[2]. Stevan P. Levitan et al reported a computer aided design tool for free-space optoelectronic systems and achieved system-level modeling[3]. The advantages of Optical MEMS sensors over Electrical sensors are high adaptability in harsh environments high temperature, chemical corrosion, strong electromagnetic interference and high-energy radiation exposure[4]. Currently, no single CAD tool completely models the complexity of these mixed tools to model, simulate, and analyze each stage of the design[4] . Hence we have chosen

Ptolemy as our framework for developing Optical MEMS based sensors. Ptolemy II is a system level design environment that supports heterogeneous modeling and design of concurrent systems. For simulating Optical MEMS devices it is essential to integrate tools with different models of computation to simulate the whole system [5]. The Ptolemy II software provides an infrastructure that allows designers explore and integrate the different models of computation [6]. It is system levels tool it. It does not provide the functionality for implementation-level simulation. But external tools based on different model of computation can be integrated into each domain and Ptolemy II can serve as semantic glue.

In this present work, the simple component of MEMS, a microcantilever is used to sense the stress. It can be operated in two modes: static and dynamic mode. In static mode, the bending of microcantilever depends upon the force or stress on the cantilever. In dynamic mode, the resonant frequency of microcantilever changes when the mass added to it. The different read out mechanisms of the microcantilever are optical readout, piezoelectric and piezoresistive [7]. Many researchers reported that the microcantilever is made of materials like Silicon, Silicon nitride and PolySilicon [8-9]. But the fabrication cost of the silicon based cantilevers is expensive. So Silicon can be replaced by a polymer which offers a shining future for the development of chemical and biological sensors. The merits of the Polymer microcantilever over silicon microcantilever are low cost, more flexibility, transparency to visible UV, easily mouldable capability, improved bio-compatibility[10]. In this paper, Polyimide and Parylene are identified as suitable polymers for microcantilevers given their low Youngs modulus, high planarity, chemical resistance and biocompatibility [11].

2 Expermental and Simulation

Laser source emits the light of wavelength (λ=850nanaometers).This laser beam is then passing through the two optical fibers separated apart axially. The cantilever structure is fixed at one end and free at other end. A slit is connected at the free end of the cantilever moves between the two optical fibers when force is applied. The deflection of the beam will be in Y direction and by virtue of this deflection the output power detected at one of the fiber ends is varied continuously from maximum to minimum though the slit arrangement as shown below. This output power variation can be calibrated according to change in minute force variation over the cantilever which in turn will constitute an accurate Optical MEMS sensor. The light coming out of the second optical fiber is detected by the photo detector.

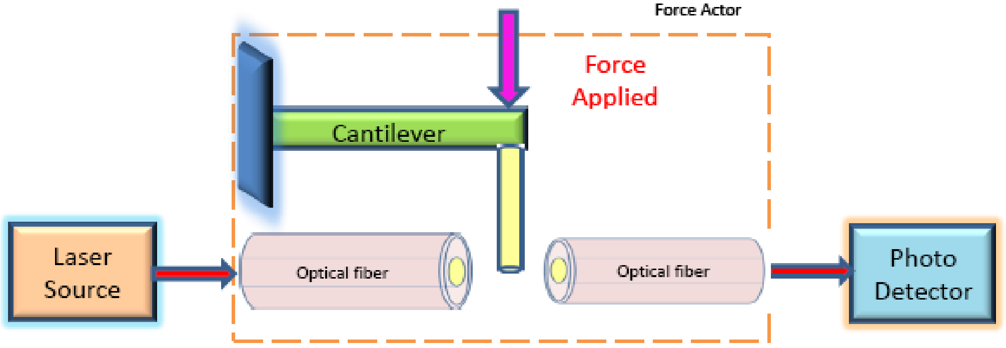

Fig. 1 Flowchart of Individual Particle Update

3 Details of Software development

In the present investigation, we have developed software codes for various actors that make an Optical MEMS Sensor in a software platform called Ptolemy. The various actors are Laser, a photo detector and a Force Actor. The individual figures of the various actors like Laser actor, Force Actor and Photodiode actor are given in the fig 2 (a)-(c) below:

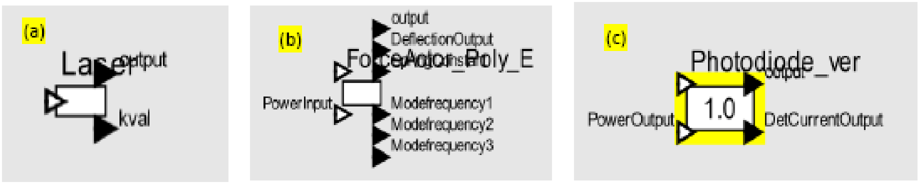

Fig. 2 (a) Laser Actor (b) Force Actor and (c) Photodiode Actor

3.1 Laser actor

The abbreviation of Laser is Light Amplification by Stimulated Emission of Radiation. Laser operates on the principle called Stimulated emission. It was postulated by Albert Einstein before 1920. This is a semiconductor laser diode (GaAs) which emits light when we apply a forward biased across the p-n junction. The laser diode actor is modelled using the mathematical equations which include Internal Power of the Laser, External Power of the Laser and Reverse Leakage current of the diode. The External Power of the laser diode is given by

$$P_o = \frac{P_{\text{int}}}{n(n+1)^2} \tag{1}$$

where n, P_{int}, P_o is refractive index of the GaAs, internal Power and external power of the Laser.

3.2 Force Actor

The Force actor made of a cantilever beam and two optical fibers. The deflection of the cantilever is modelled using stoneys equation, spring constant and the three modes of the resonant frequency. The optical fiber actor is created using the power output detected at the second fiber and the loss of light due to the force applied on the cantilever.

3.2.1 Cantilever Beam

Micro cantilever is a widely used component in micro electro mechanical system devices [12]. Cantilever is a type of beam fixed at one end and suspended freely at the other end and the beam is originally straight. The equation (2) is the Stoneys formula [13], which relates cantilever end deflection δ to applied stress σ:

$$\delta = \frac{3\sigma(1-\nu)}{E}(\frac{L}{t})^2 \tag{2}$$

where δ,σ,L,t,E,ν are deflection, stress, length of the Cantilever beam, Youngs Modulus, Poissons ratio.

The spring constant (k) of the cantilever beam is given by

$$k = \frac{Ewt^3}{4L^3} \tag{3}$$

where E, w, t and L are the Youngs modulus, width , thickness and length of the cantilever beam.

The frequency at which a cantilever tends to oscillate in the absence of any force is the eigen frequency .The eigen frequency of a cantilever beam [14] can be find out from the optimized cantilever geometry for the L and t and density , for the two sensors is given by

$$f = \alpha_n \frac{t}{L^2}\sqrt{\frac{E}{\rho}} \tag{4}$$

$$\alpha_n = \frac{1}{4\pi\sqrt{\varepsilon}}\lambda_n^2 \tag{5}$$

where λ_n=1.8751, 4.6941, 7.8547 ......

3.2.2 Optical Fibre

We have designed two fibres with core diameter $2a$= 175m coupled longitudinally such that the free end of the cantilever will move the slit vertically down between the fiber ends as force is applied on it. As a result the light coupled from fiber1 to fiber2 decreases gradually as the amount of force increases.

There are two formulas used for calculating loss and power detected at the second at the second fiber is given below.

$$P_{out} = P_{in}\left[1 - \left(\frac{w}{2a}\right)\right] \tag{6}$$

$$Loss = 20\log_{10}A \tag{7}$$

where A stands for ratio of P_{out}/P_{in}. Loss is a function $f(w)$, where w is the cantilever deflection, which is numerically equal to $w/2a$, where $2a$ is the fiber diameter.

3.3 Detector Actor

A photodiode is a semiconductor device, with a p-n junction and an intrinsic layer between p and n layers. The photo detector used is a reverse biased photodiode (PD) which converts the input optical power into the photo current (I_p). The following formulas are applied to create a detector actor:
The Photocurrent is given by

$$I = RP_{out} \tag{8}$$

The Responsivity measure the electrical output per optical input of the photodiode is given by

$$R = \frac{\eta q \lambda}{hc} \tag{9}$$

where η, q, h, c, λ are Internal quantum efficiency, Charge of electron, Plancks constant, Velocity of light in vacuum, Wavelength of light.

Using the above actors, the Optical MEMS sensor model are created in the Ptolemy framework as shown in the fig 3 and fig 4. In the present work, two Force actors were created using the same geometrical parameters but the cantilever beam is made of different polymer materials like Polyimide and Parylene. The maximum stress sensed by the cantilever is measured for two different materials of the cantilever beam. The material properties of the Cantilever beam include the Youngs Modulus (E), Poisson ratio (ν) and density (ρ) is given in the table 1 :

Table 1 Material Properties of the Cantilever beam

Material Properties	**Polyimide**	**Parylene**
Youngs Modulus (GPa)	3.2	2.8
Poison Ratio	0.42	0.4
Density (Kg/m3)	1300	1289

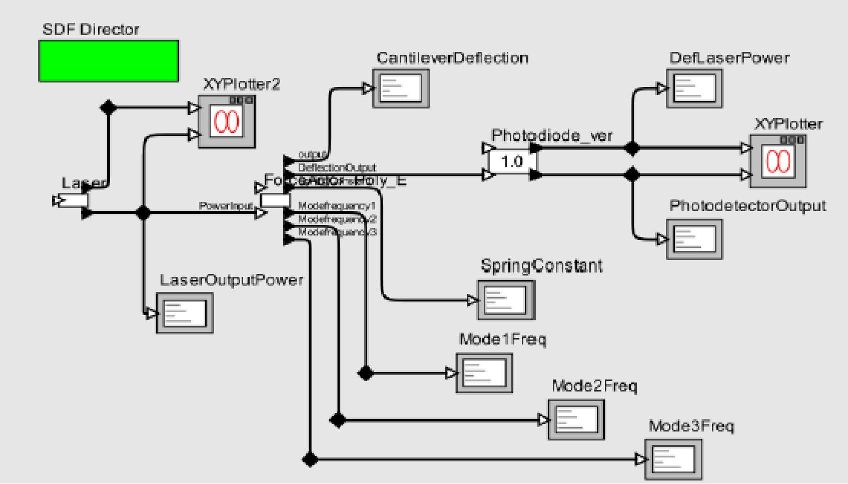

Fig. 3 Model of the Optical MEMS Sensor(Polyimide material) using Ptolemy II

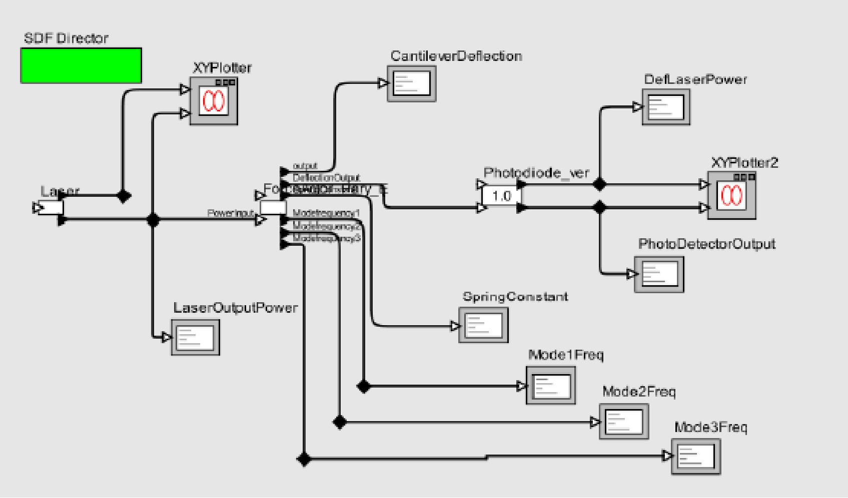

Fig. 4 Model of the Optical MEMS Sensor (Parylene material) using Ptolemy II

3.4 Model the MEMS Cantilever beam using COMSOL

COMSOL Multiphysics version 5.0, a commercial FEM tool for MEMS was used to develop a finite element model [15] of the Polymer cantilevers. In the present work, the cantilever beam modelled using cost effective open source Ptolemy Software and its eigen frequency of the first three modes are compared with the rectangular beam of two different materials Polyimide and Parylene using the using Comsol Software. The free tetrahedral meshing is applied.

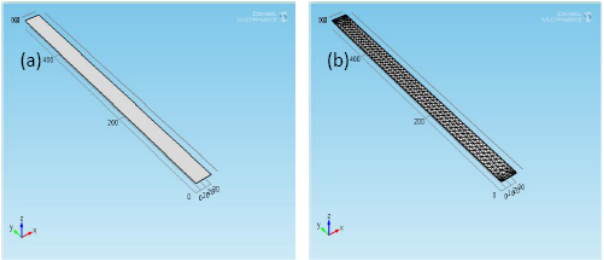

Fig. 5 5(a) Model of the rectangular Cantilever Beam using COMSOL, Fig 5(b) Mesh model of the Cantilever Beam

4 Results and Discussion

4.1 Optical MEMS Sensor Using Ptolemy

In the optical MEMS sensor model, the Laser diode is modelled the fig.6 (a) and fig 7(a) represents the output power of the Laser and Output current of Laser Diode. The output power increases linearly with the applied current, when the applied current is larger than the threshold current. When the force applied on the cantilever, the cantilever bends and light passing from the optical fiber 1 to optical 2 is blocked based on the amount of force applied. The range of the force applied and the deflection of the cantilever is recorded for the two Optical Sensors are tabulated in table 2. In fig.6 (b)-(d) and fig. 7(b)-(d), the sample of the force applied in the cantilever and corresponding deflection of the cantilever is recorded, then the deflected Laser Power is converted into current by the photodiode and plotted in the graph.

4.2 Comsol Cantilever Beam Result

The results of the first three modes of the cantilever beam of two materials modeled using COMSOL software are shown in the fig 8(a)-(f). The analytical values of the eigen frequencies are compared with Eigen frequencies of the two cantilevers modelled using Comsol are tabulated in the table 3 and the same is represented using bar chart is shown in fig 9(a)-(b).

5 Optimization of the Geometrical Parameters

The different lengths (200 μm, 300 μm, 400 μm, 450 μm, 500 μm) of the two different materials of the cantilever are kept constant and the thickness of the cantilever is varied from 0.5 μm to 3.0 μm. For each length and the maximum stress/force is recorded for each simulation is shown in table 4 and table 6 and the results are plotted is shown in figure 10. (a)-(f). For different thickness (t=0.5 μm, 1.0 μm,1.5 μm,2.0 μm,2.5 μm and 3.0 μm), the length is varied from 200 μm to 500 μm for each thickness and the maximum stress/force is recorded for each

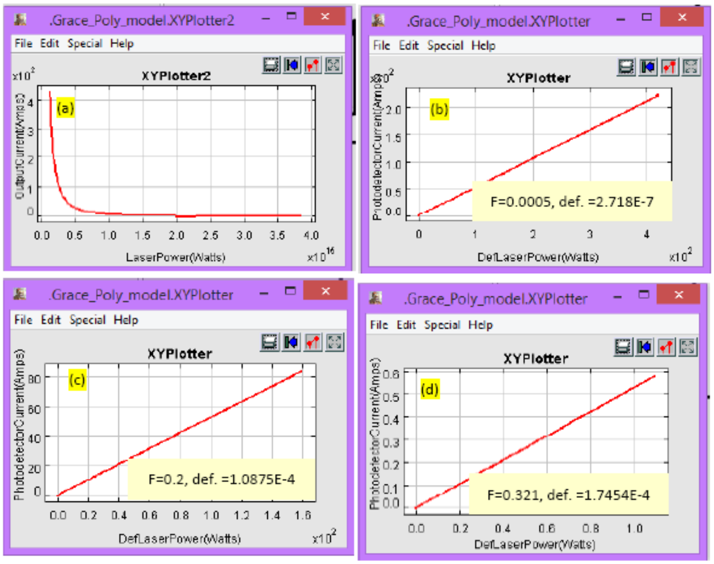

Fig. 6 Simulation result of the Polyimide Optical MEMS Force Sensor (a) Output Power of Laser diode (b), (c) and (d) Deflected Laser Power Vs Output Current at the photodetector

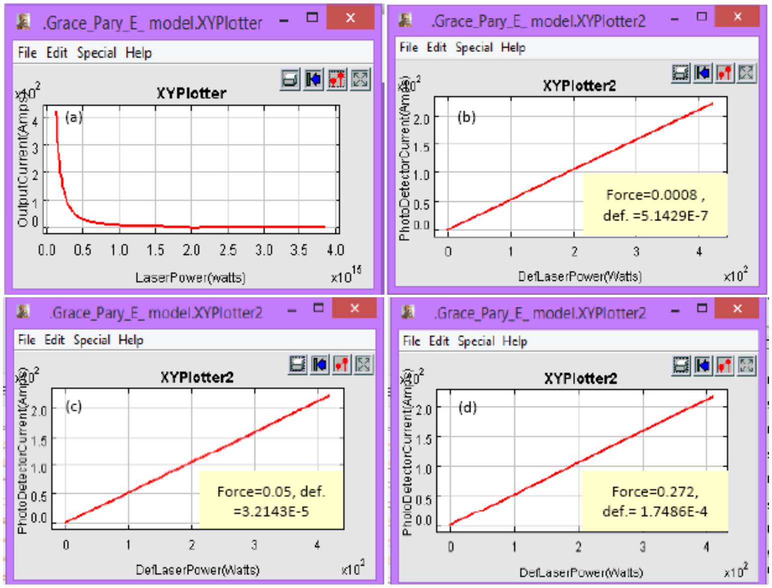

Fig. 7 Simulation result of the Parylene Optical MEMS sensor1 (a) Output Power of Laser diode (b), (c) and (d) Deflected Laser Power Vs Output Current at the photo detector

Table 2 Stress/Force Applied vs. Cantilever deflection of the Two Optical MEMS Sensor using Ptolemy

Polyimide Optical MEMS Sensor		**Parylene Optical MEMS Sensor**	
Stress/force Applied (N/m)	**Cantilever Deflection**	**Stress/force Applied (N/m)**	**Cantilever Deflection**
0.0005	2.72E-07	0.0003	1.93E-07
0.05	2.72E-05	0.05	3.21E-05
0.2	1.09E-04	0.1	6.43E-05
0.321	1.75E-04	0.272	1.75E-04
0.322	1.75E-04	0.273	1.76E-04

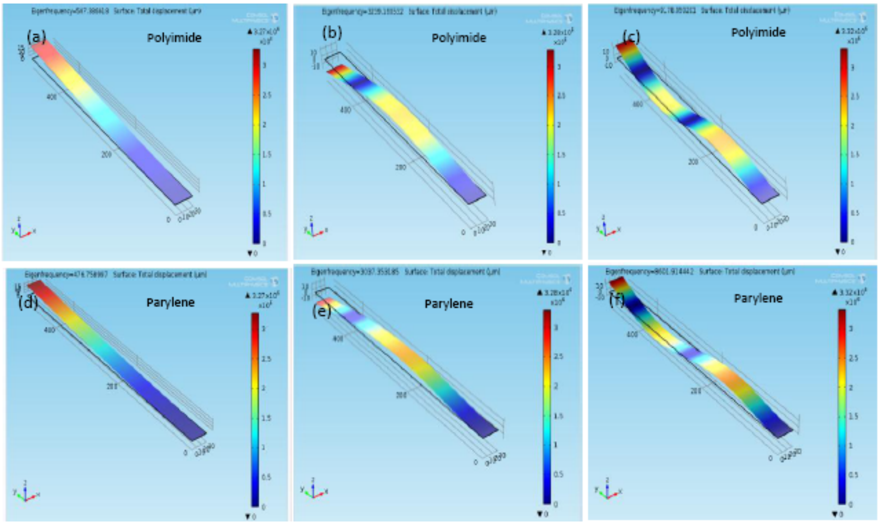

Fig. 8 Eigen frequency of the result of the rectangular Cantilever beam1 (a)-(c) and (d)-(f)Cantilever beam2 using Comsol

Table 3 Comparison of Eigen frequency values using Ptolemy and Comsol software

Modes of Eigen frequency	**Polyimide Cantilever**		**Parylene Cantilever**	
	Ptolemy(KHz)	COMSOL(KHz)	Ptolemy(KHz)	COMSOL(KHz)
1	0.5071	0.5074	0.4764	0.4678
2	3.178	3.2392	2.986	3.037
3	8.899	9.1789	8.3597	8.602

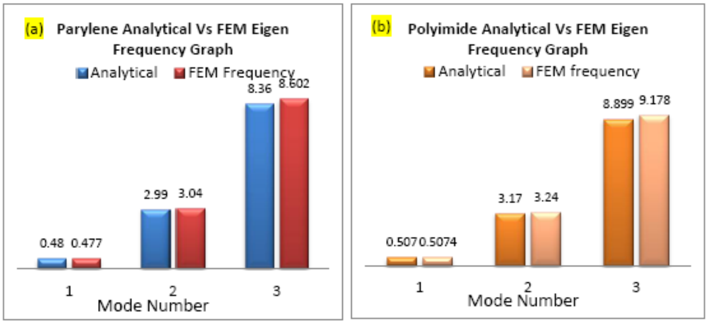

Fig. 9 (a-b): Comparison of the modes Vs. Eigen frequency of the Polyimide and Parylene Cantilever beam using Ptolemy and COMSOL

Table 4 Different length of the Cantilever beam Vs. Maximum Stress/force applied at constant thickness of the Polyimide Optical MEMS Force Sensor

Polyimide Optical MEMS Sensor					
Cantilever Thickness (μm)	**Max. stress/force applied (N/m)**				
	L=200 μm	**L=300 μm**	**L=400 μm**	**L=450 μm**	**L=500 μm**
0.5	2.01	0.88	0.502	0.397	0.321
1	8.045	3.57	2.011	1.588	1.287
1.5	18.1	8.04	4.52	3.575	2.89
2	32.1	14.29	8.04	6.35	5.14
2.5	50	22.3	12.56	9.93	8.04
3	72.3	32.17	18.08	14.3	11.58

Table 5 Different thickness of the Cantilever beam Vs. Maximum stress/force applied at constant Length of the Polyimide Optical MEMS Sensor

Polyimide Optical MEMS Sensor						
Cantilever Length (μm)	**Max. stress/force applied (N/m)**					
	t=0.5μm	t=1.0μm	t=1.5μm	t=2.0μm	t=2.5μm	t=3.0μm
200μm	2.01	8.045	18.1	32.1	50	72.3
300μm	0.88	3.57	8.04	14.29	22.3	32.17
400μm	0.502	2.011	4.52	8.04	12.56	18.08
450μm	0.397	1.588	3.575	6.35	9.93	8.04
500μm	0.321	1.287	2.89	5.14	8.04	11.58

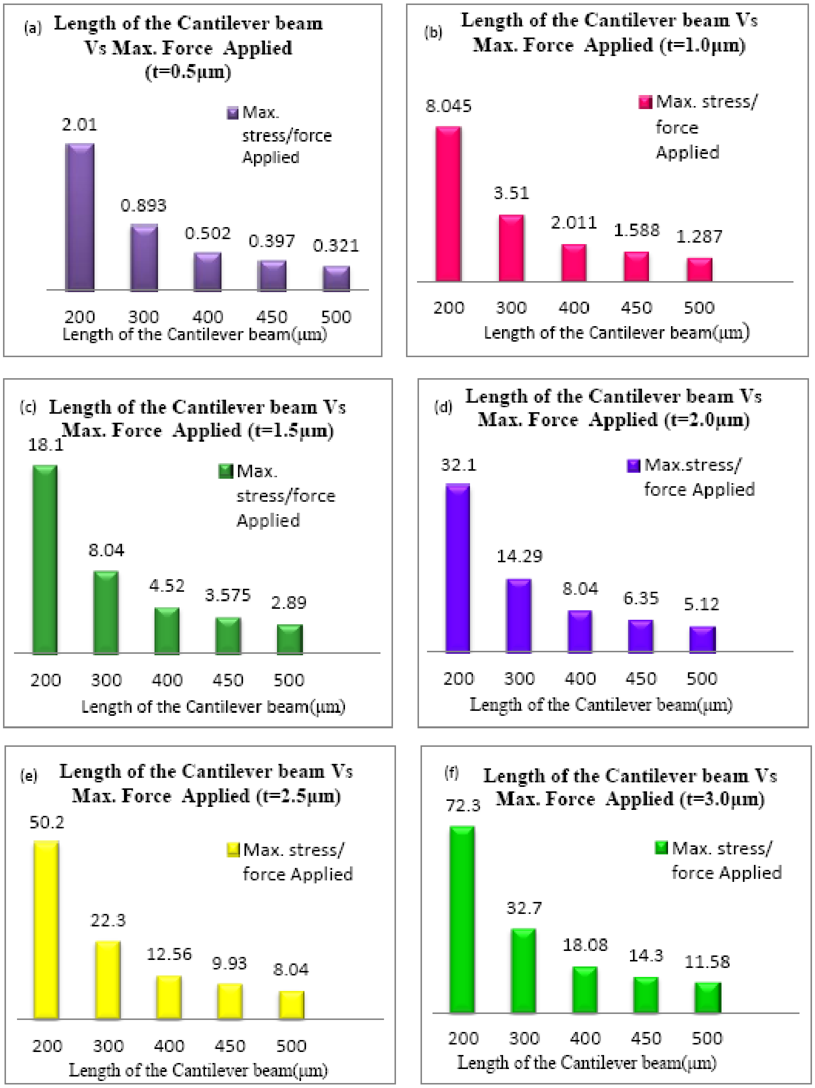

Fig. 10 (a)-(f) Different length of the Cantilever beam Vs Maximum stress/force applied of the Polyimide Optical MEMS Sensor at constant thickness

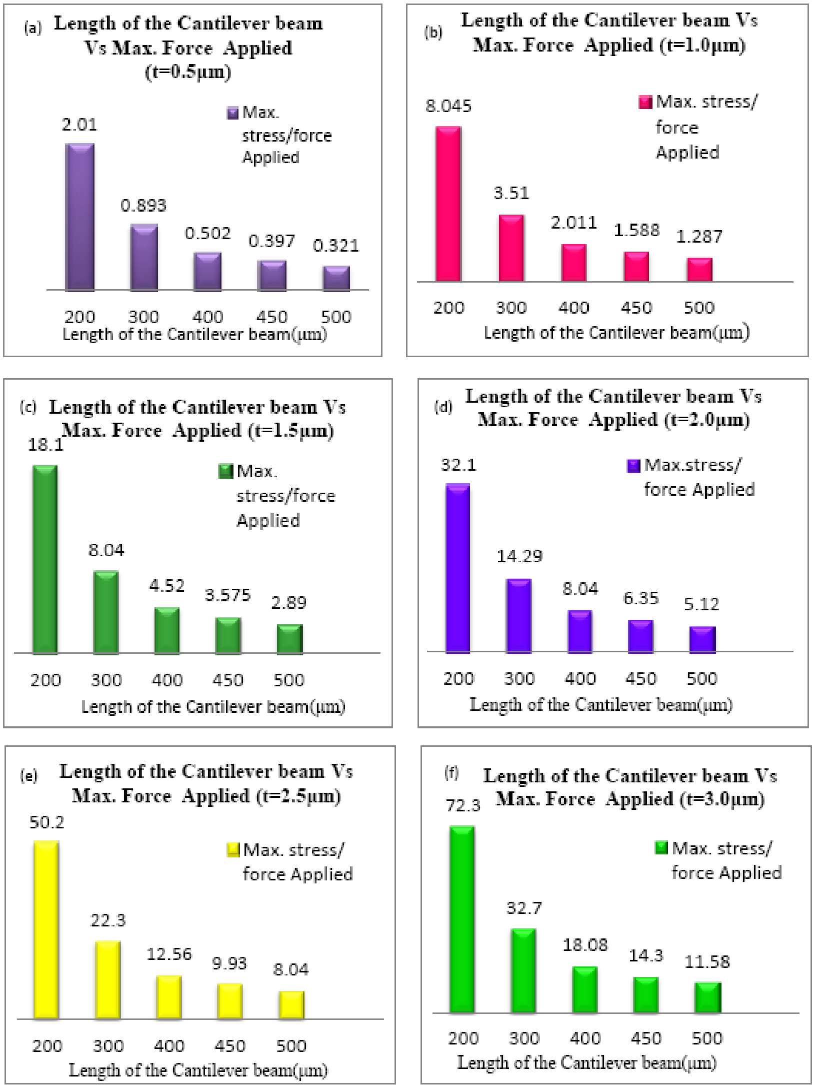

Fig. 11 (a)-(f) Different length of the Cantilever beam Vs Maximum stress/force applied of the Polyimide Optical MEMS Sensor at constant thickness

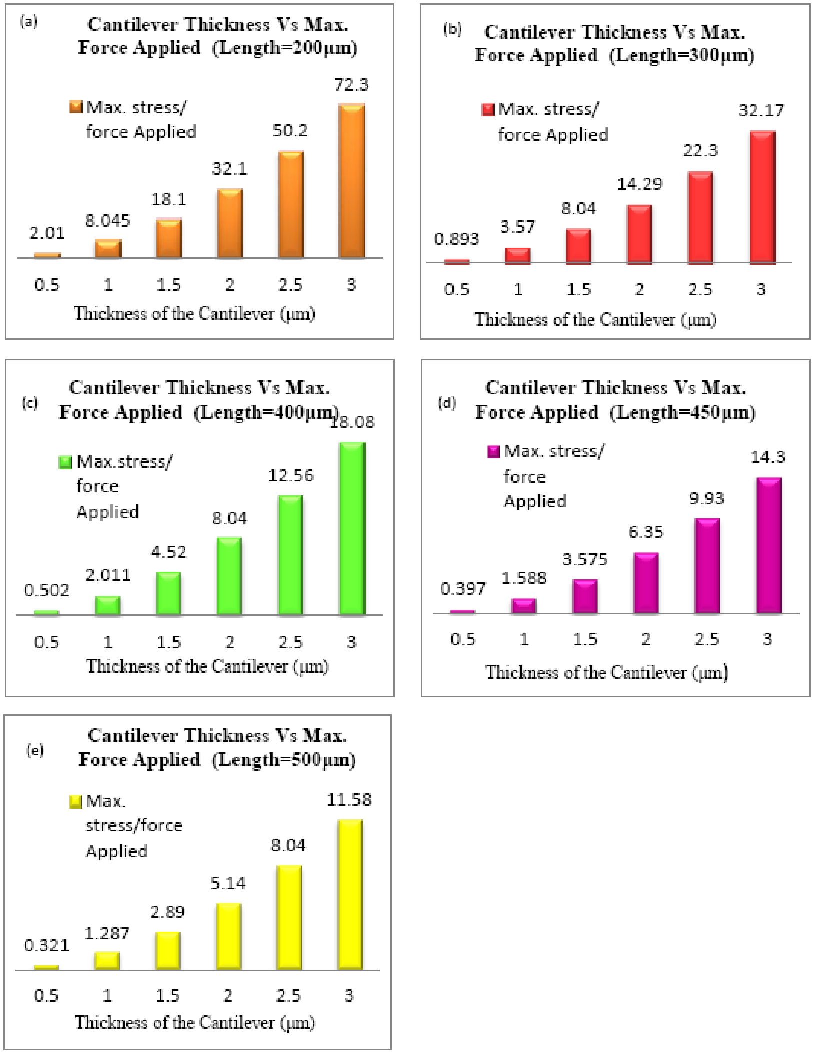

Fig. 12 (a)-(f) Different thickness of the Cantilever beam Vs. Maximum stress/force applied of the Polyimide Optical MEMS Sensor at constant Length

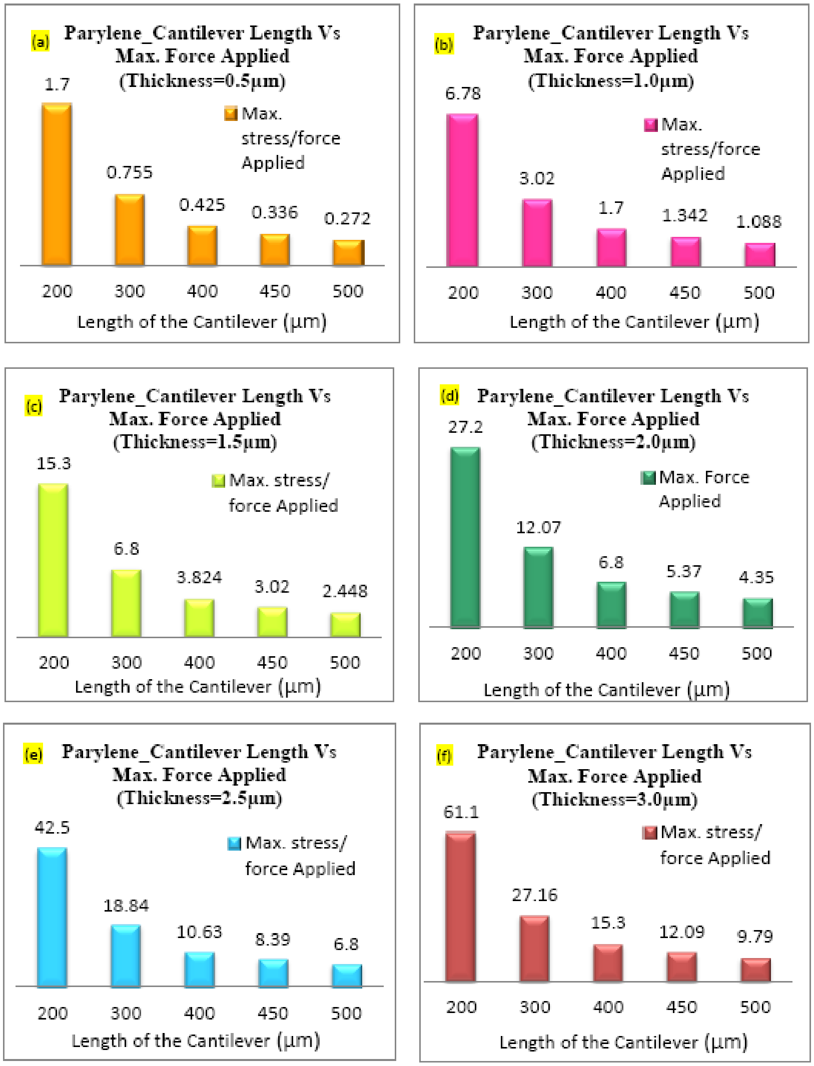

Fig. 13 (a)-(f) Different length of the Cantilever beam Vs. Maximum stress/force Applied at constant thickness of the Parylene Optical MEMS Sensor

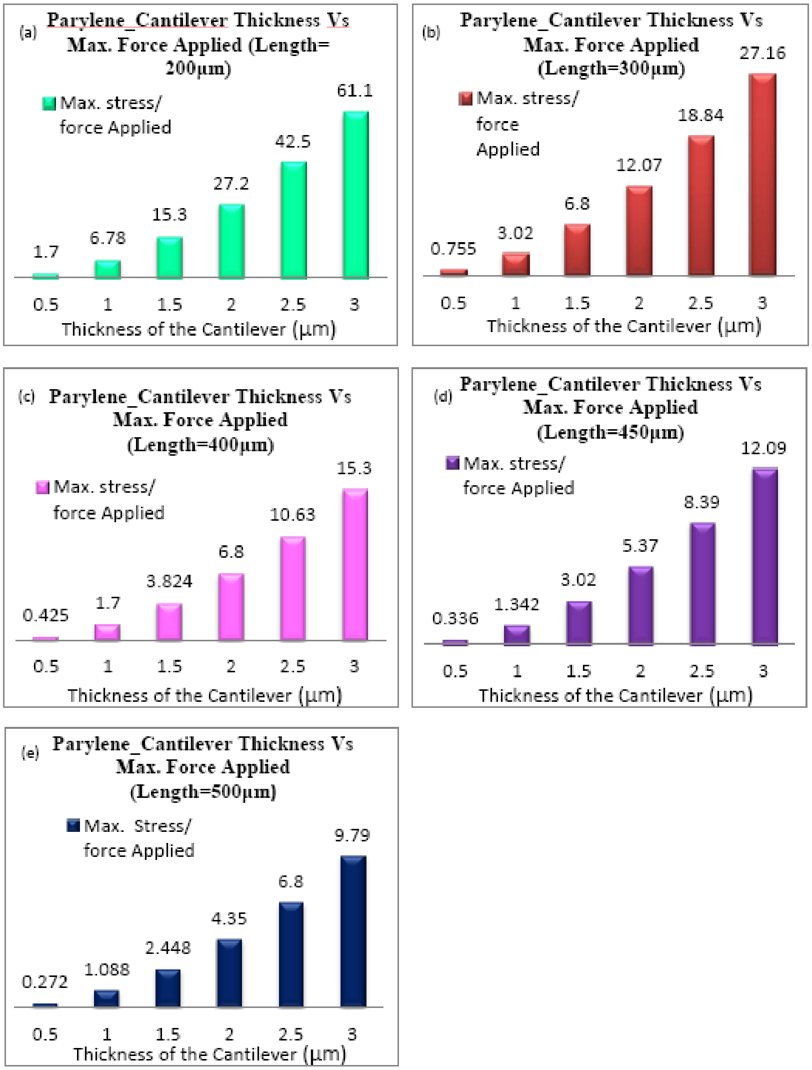

Fig. 14 (a)-(e) Different thickness of the Cantilever beam Vs. Maximum stress/Force Applied at constant length of the Parylene Optical MEMS Force Sensor

Table 6 Different length of the Cantilever beam Vs. Maximum stress / force applied at constant thickness of the Parylene Optical MEMS Sensor

Parylene Optical MEMS Sensor					
Cantilever Thickness (μm)	**Max. stress/force applied (N/m)**				
	L=200μm	**L=300μm**	**L=400μm**	**L=450μm**	**L=500μm**
0.5	1.7	0.755	0.425	0.336	0.272
1	6.78	3.02	1.7	1.342	1.088
1.5	15.3	6.8	3.824	3.02	2.448
2	27.2	12.07	6.8	5.37	4.35
2.5	42.5	18.84	10.63	8.39	6.8
3	61.1	27.16	15.3	12.09	9.79

Table 7 Different thickness of the Cantilever beam Vs. Maximum stress/force applied at constant Length of the Parylene Optical MEMS Sensor

Parylene Optical MEMS Sensor						
Cantilever Length (μm)	**Max. stress/force applied (N/m)**					
	t=0.5μm	t=1.0μm	t=1.5μm	t=2.0μm	t=2.5μm	t=3.0μm
200 μm	1.7	6.78	15.3	27.2	42.5	61.1
300 μm	0.755	3.02	6.8	12.07	18.84	27.16
400 μm	0.425	1.7	3.824	6.8	10.63	15.3
450 μm	0.336	1.342	3.02	5.37	8.39	12.09
500 μm	0.272	1.088	2.448	4.35	6.8	9.79

simulation is shown in table 5 and table 7 and the results are plotted is shown in figure 11. (a)-(f). From the recorded values, low stress/force is achieved at the length 500 μm and the thickness is 0.5m for both the sensors.

6 Conclusion

Different actors like Laser actor, Force actor and photodetector have been developed and added in Ptolemy framework. The physical functioning of each component of the Optical MEMS Force Sensor device has been simulated using these actors. The results have been presented. The two optical MEMS force sensor are simulated in Ptolemy II. The Parylene Optical MEMS sensor can sense the low stress/force in the range of 0.0003 N/m to 0.272 N/m with the present fiber optic setup. The Eigen frequency of the two cantilever beam is modelled using open source Ptolemy II and the three modes of Eigen frequencies are compared with the results of the COMSOL. The low stress/force is measured for the optimized length (500 μm) and the thickness (0.5 μm) is found by varying the thickness and length of the Cantilever using Ptolemy.

7 Acknowledgement

We are thankful for support by the NPMASS MEMS Design Centre, SENSE, VIT University for doing this project.

References

[1] E. Ollier(2002), "Optical MEMS Devices Based on Moving Waveguides", *IEEE J.Sel. Topics Quantum Elect*, vol. 8, no. 1, pp. 155C62.

[2] Selvarajan, A and Pattnaik, Prasant Kumar and Badrinarayana, T and Srinivas, T (2006), "A comparative study of MOEM pressure sensors using MZI, DC, and racetrack resonator IO structures", *In Proceedings SPIE International Conference on Smart Structures and Materials 2006:Smart Electronics, MEMS, BioMEMS, and Nanotechnology*, pages Vol.61726, 61721A, San Diego, California, USA.

[3] Levitan, S.P., Kurzweg, T.P., Marchand, P.J., Rempel, M.A., Chiarulli, D.M., Martinez, J.A, Bridgen, J.M.,Fan, C. and McCormick, F.B.(1998), " Chatoyant: a computer-aided design tool for free-space optoelectronic systems", *Applied Optics*,Vol. 37, No. 26, pp. 6078-6092.

[4] T.P. Kurzweg, J.A. Martinez, S.P. Levitan, P.J. Marchand and D.M. Chiarulli(2001), "Dynamic Simulation of Optical MEM Switches", *Optics in Computing (OC'01)*,Lake Tahoe, NV, pp. 35-37.

[5] J. Davis, etc.(1999), "Heterogeneous Concurrent Modeling and Design in Java", UCB/ERL Memorandum M99/ 40, Dept. of EECS, University of California, Berkeley, CA 94720.

[6] J. Liu , B. Wu, X. Liu and E. A. Lee(2001), "Interoperation of heterogeneous CAD tools in Ptolemy II", Department of Electrical Engineering and Computer Science, University of California, Berkeley, CA 94720 U.S.A.*Journal of Modeling and Simulation of Microsystems*,Vol. 2, No. 1, pp. 1-10.

[7] P.Sangeetha and A.Vimala Juliet, "MEMS Cantilever Based Immunosensors for Biomolecular Recognition ", *International Journal of Computer Technology and Electronics Engineering (IJCTEE)*, Vol. 2, No. 1.

[8] M. Maute, S. Raible, F.E. Prins, D.P. Kern, H. Ulmer, U.Weimar and W. Gopel(1999), “Detection of volatile organic compounds VOCs/ with polymer-coated cantilevers”, *Sensors and Actuators* , pp.505C511.

[9] Denis Spitzer, Thomas Cottineau, Nelly Piazzon, Sbastien Josset, Fabien Schnell, Sergey Nikolayevich Pronkin, Elena Romanovna Savinova and Valerie Keller(2012), “Research on the Sustainable Utilization of Water Resources of Jinan City”, *Bio-Inspired Nanostructured Sensor for the Detection of Ultralow Concentrations of Explosives*,Angew. Chem. Int. Ed. pp.5334C5338.

[10] B G Sheeparamatti, M S Hebbal, R B Sheeparamatti, V B Math and J S Kadadevaramath(2006), ‘Simulation of Biosensor using FEM”, *Journal of Physics: Conference Series*, Vol.34, pp.241C246.

[11] Richardson R, J.A. Miller and W.M. Reichert(1993), *Biomaterials.*, Vol.(14), pp.627C635.

[12] Subhashini. S and Vimala Juliet. A(2013), “Resonance Based Micromechanical Cantilever For Gas Sensing”, *International Journal of Network Security and Its Applications (IJNSA)*, Vol.44, No.W12420.

[13] Stoney G(1909), The tension of metallic films deposited by electrolysis, Proc R Soc Lond Ser A 1909; 82: 172-5.. Stoney, G. Gerald. “The Tension of Metallic Films Deposited by Electrolysis”, *Proceedings of the Royal Society of London*,pp.40-43.

[14] Suryansh Arora, Sumati, Arti Arora and P.J.George (2012), “ Design Of Mems Based Microcantilever Using Comsol Multiphysics”, *International Journal of Applied Engineering Research*,Vol.7 No.11. pp.1-3.

[15] G. Louarn and S. Cuenot(2008), “ Finite Element Modelling of Microcantilevers Used as Chemical Sensors”, *Recent Advances in Modelling and Simulation*,pp.207-222.

Corresponding author

Rajasekhara Babu M can be contacted at: rajababu.m1@gmail.com