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Research Article

Some Aspects of Analysis of a Micromirror

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Abstract: Micromirror is a very small mirror based on the principle of Micro Electro Mechanical Systems (MEMS). Micromirror application in areas like laser scanning displays, DLP Projection system and HDTV are realized using MEMS technology. In this study, an electrostatically controlled micromirror is designed using COMSOL multi-physics software. The structural and mechanical properties of the actuation mechanism of various shapes of a micro-mirror will be studied. The base materials used will include Copper, Silicon and Aluminum. To make the cantilever more efficient, the structural steel was introduced along with the base materials listed above so as to obtain the displacement of the mirror. In order to evaluate the mirror further, the analytical formulation for Capacitance and Torque are developed and compared to the calculated theoretical values. The final results are shown as a range of wavelength, which will be obtained taking into consideration the tilting angle obtained from various materials used for the designing of the mirrors.

Keywords: COMSOL, DLP, DMD, electrostatic, HDTV, MEMS

INTRODUCTION

During the last ten years, the development of Micro Electro Mechanical Systems (MEMS) technology has taken a huge leap in the field of communication and medicine industries, academia and automotive and optical industries. This huge improvement was possible by reduction in the mass and size of various MEMS devices which further help in improving the performance of these devices. Out of all these applications, Optical Coherence Tomography (OCT) for an endoscope, optical switch arrays for communications, Confocal Laser Scanning Microscopy (CLSM) and digital micro-mirror devices for Digital Micromirror Device DMD for Digital Light Process (DLP) Projection, find varied uses in the field of optical industries. Be it the case in the form of a micro lens array where a computer-controlled digital micromirror chip modulates incoming light as it is reflected into a vat of liquid photosensitive polymer (Cuiling and Mehryl, 2014; Van Kessel *et al*., 2011) or any other application, micro mirrors are here to stay. Digital micro mirror device, or DMD is the core of DLP projection technology (Park *et al*., 2008; Mamat *et al*., 2013) and was invented by Dr. Larry Hornbeck and Dr. William E. "Ed" Nelson of Texas Instruments (TI) in 1987. Micromirror devices are based on small mirrors which vary in the range of millimeters. They may be used in projectors inertial sensors. These mirrors used Micro Electro Mechanical System, so that their states (on/off) are controlled by applying a voltage between the two electrodes around the mirror array. Electrostatic forces also controls micro-mirror (Bansal and Singh, 2014; Wei-Hsin *et al*., 2008a) It is typically quite small and arrays of such devices can be implemented in a projection system. Actuation mechanisms like electrostatic, piezoelectric electromagnetic and electrothermal have been exclusively used in micromirror designs (Wei-Hsin *et al*., 2008b). For this simulation, we used Solid Mechanics, electrostatic and Electromagnetic Wave mechanism.

LITERATURE REVIEW

A lot of work in the field of MEM micromirror is in the process. Where an ample amount of work has been carried out starting from the MEMS based DLP Processing which is being studied till today (Hornbeck, 1996; Katal *et al*., 2013). Along with it, a lot of importance has also been given to various applications of a micromirror (Shahid *et al*., 2014) and its has been further classified as an optical system (Solgaard *et al*., 2014). But not much work has been has been carried out so as to explain the basic characteristics of MEMS micromirror in detail which has been carried out in this study.

DESIGN AND SIMULATION OF A MICROMIRROR

The model created uses 3D structural analysis using COMSOL software. Solid Mechanics is used to

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design the Micro mirror. Its central portion is surrounded and supported by two cantilever beams. It is designed in such a manner so that one end of the cantilever beam is connected to the central portion while the other end is kept free (Wei-Hsin *et al*., 2008b; Park *et al*., 2010). Before starting the simulation, the characteristics of the materials were selected and studied from the material section depending on the value of Young's Modulus and Poissoin's Ratio (COMSOL model Library). The materials used are as shown in Table 1. For all the simulated designs, 1 Pa initial stress was used.

Table 1: Parameters for various shapes of a micromirror

	Square-Al, Si, Cu			Rectangle-Al, Si, Cu			Circle-Al, Si, Cu		
Parameters									
L/2/d/2 µm	0.5	0.5	0.5	0.4	0.4	0.4	0.5	0.5	0.5
g (mm)	0.3								

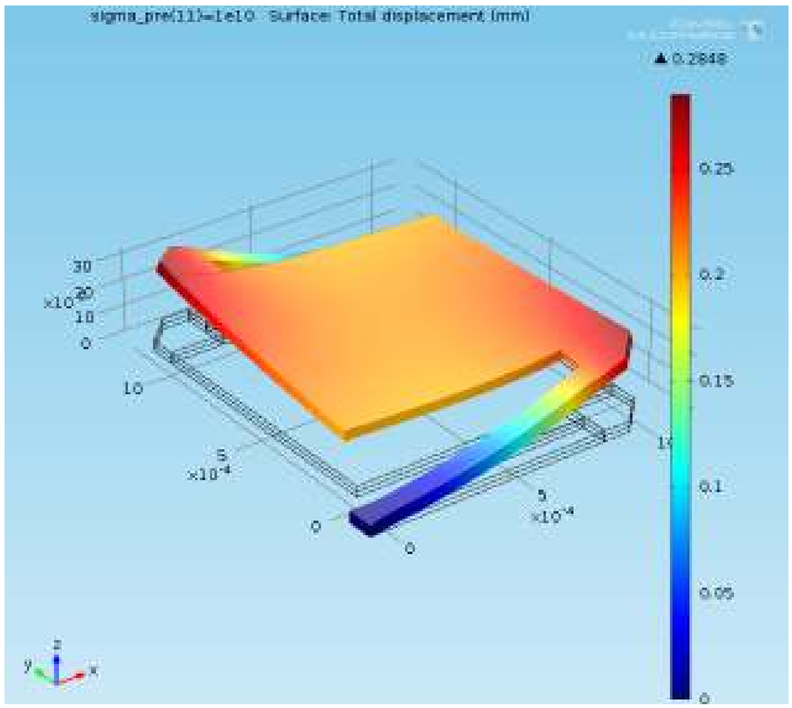

Fig. 1: Simulation using COMSOL-for aluminum and structural steel-square shape

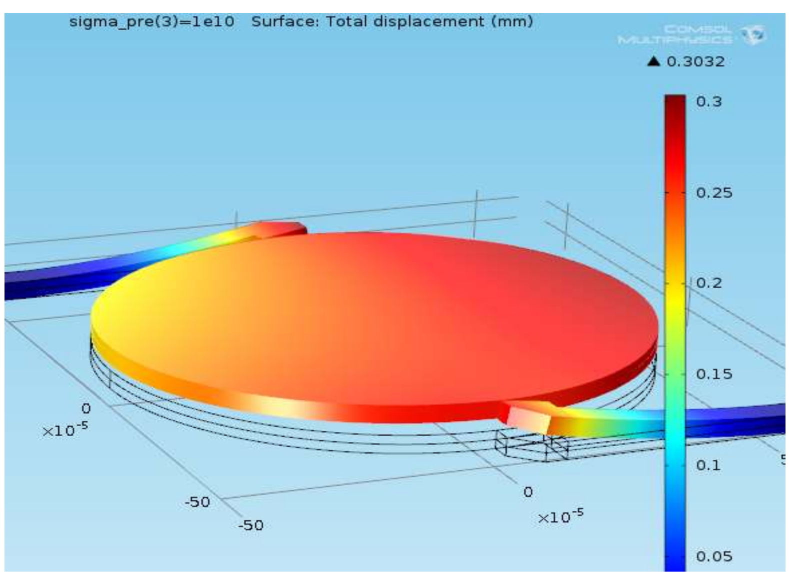

Fig. 2: Simulation using COMSOL-for aluminum and structural steel-circular shape

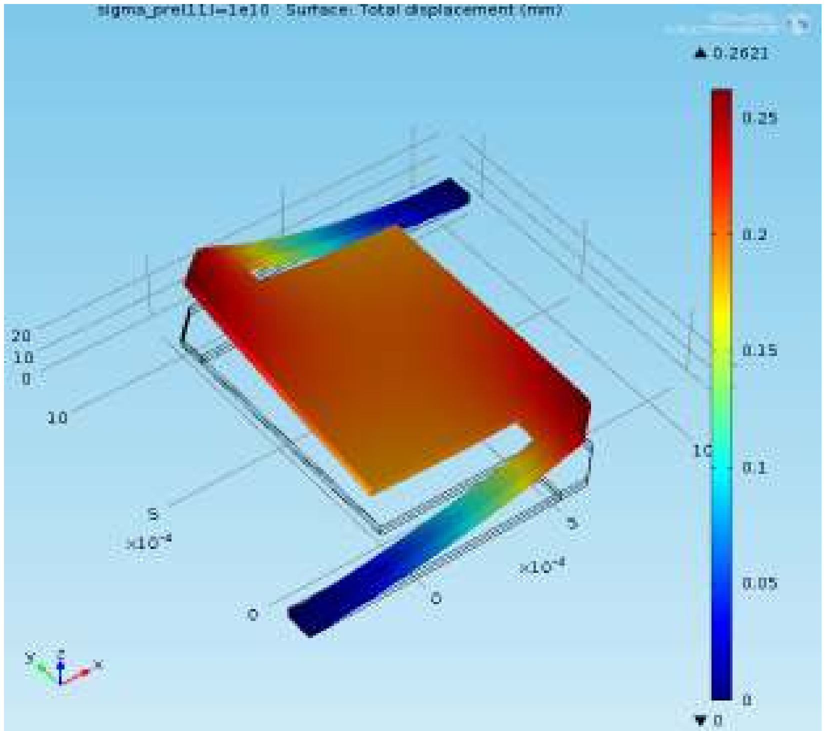

Fig. 3: Simulation using COMSOL-for aluminum and structural steel-rectangular shape

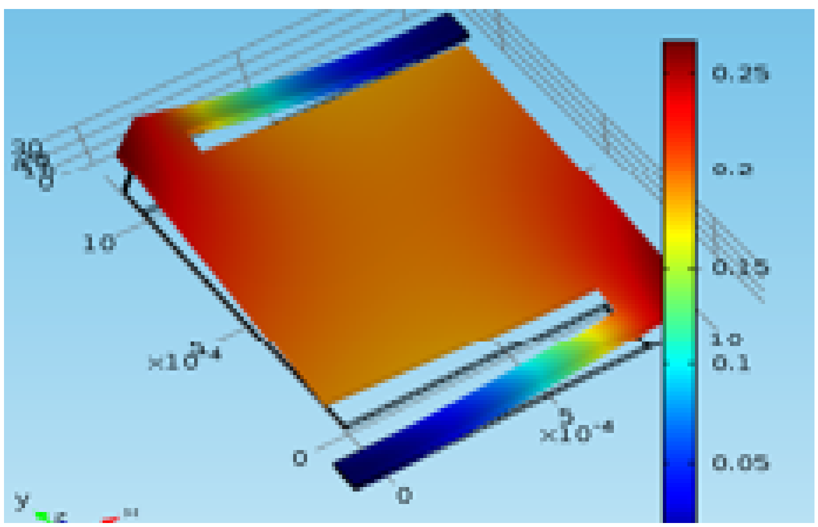

Fig. 4: Simulation using COMSOL-for copper and structural steel-square shape

SIMULATION RESULTS

The model created uses 3D structural analysis using COMSOL software. Solid Mechanics was used to design the Micromirror. Its central portion is surrounded and supported by two cantilever beams (Electrodes). One end of the cantilever beam is connected to the central portion while the other end is kept free. The parameters used to design the mirror are shown in Table 1. In the table, g represents the air gap taken between the electrode and the mirror surface and L/2 and d/2 is the half of length and diameter taken for the respective shapes. Half value is taken because the tilt occurs from the central portion of the mirror.

Using these parameters, the mirrors were designed which can be seen in Fig. 1 to 9. The displacement obtained in the figures is clearly visible by its tilting angle. Figure 1 to 3 represent the displacement obtained for the square shape. The blue color is the area where the strain is the lease while the red color determines the highest strain. Similar characteristics

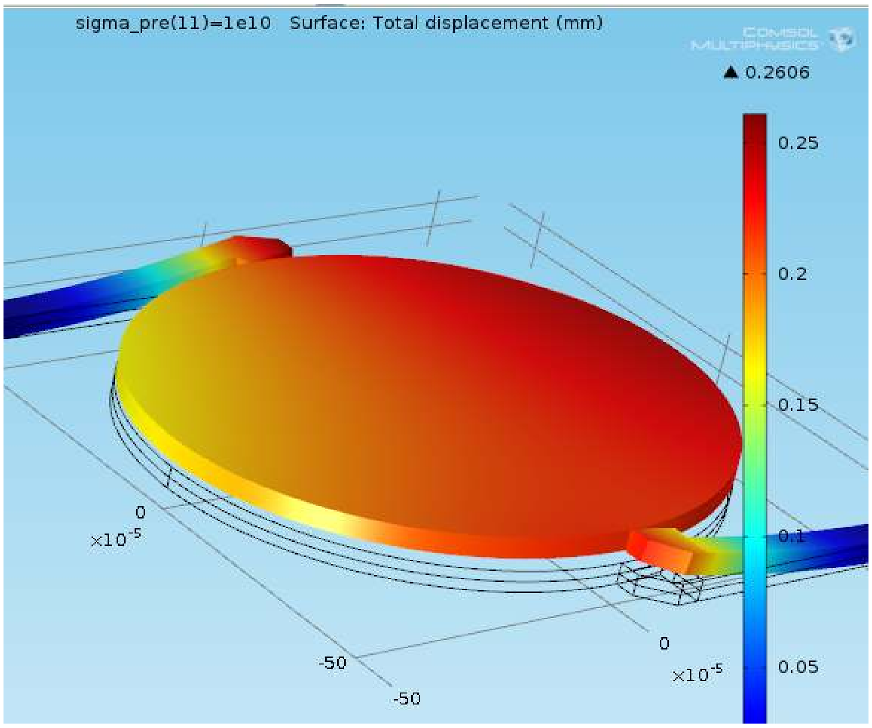

Fig. 5: Simulation using COMSOL-for copper and structural steel-circular shape

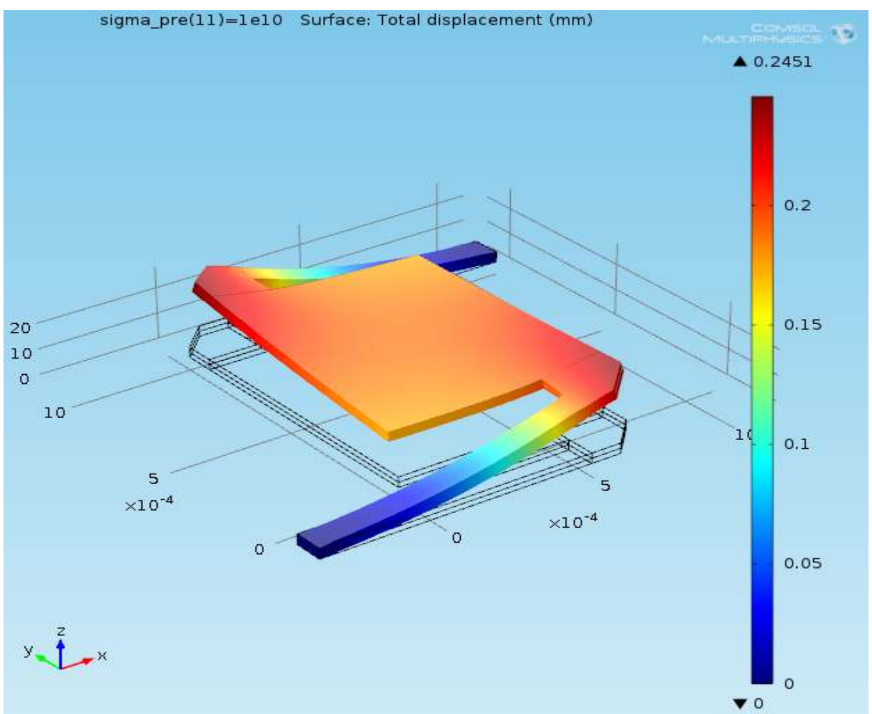

Fig. 6: Simulation using COMSOL-for copper and structural steel-rectangular shape

can be seen for Figure 3 to 6 and 7 to 9 as they also represent the displacement of the mirror for Copper and steel respectively. They values of displacement obtained is shown in Table 2. It is clear that the surface deformation is different for different shapes and materials of the micromirror. The combination of Aluminum and Structural steel suffers from high deformation and stress for all the three shapes used and the least displacement is obtained by the combination of Silicon and Structural

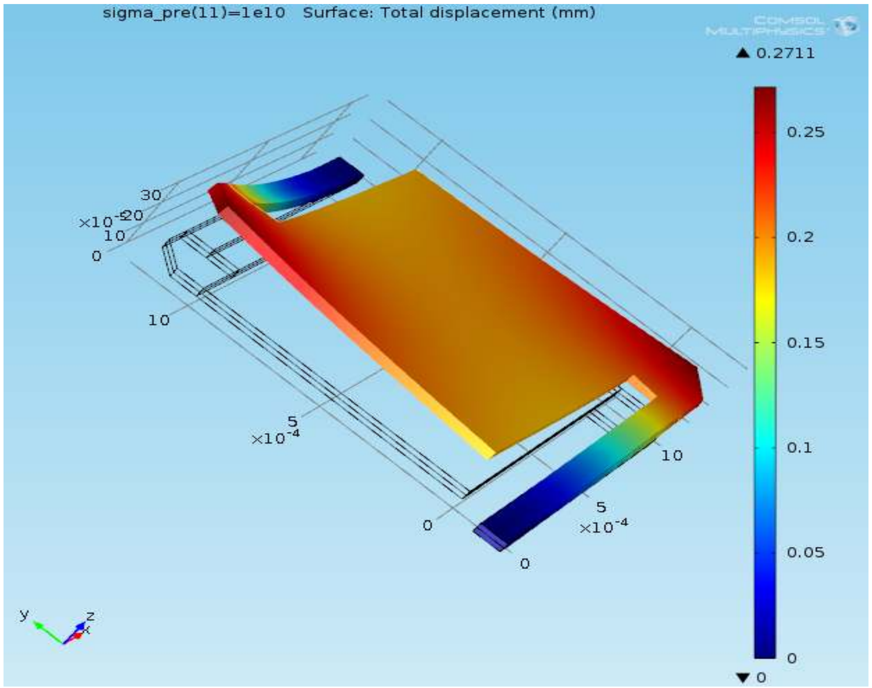

Fig. 7: Simulation using COMSOL-for silicon and structural steel-square shape

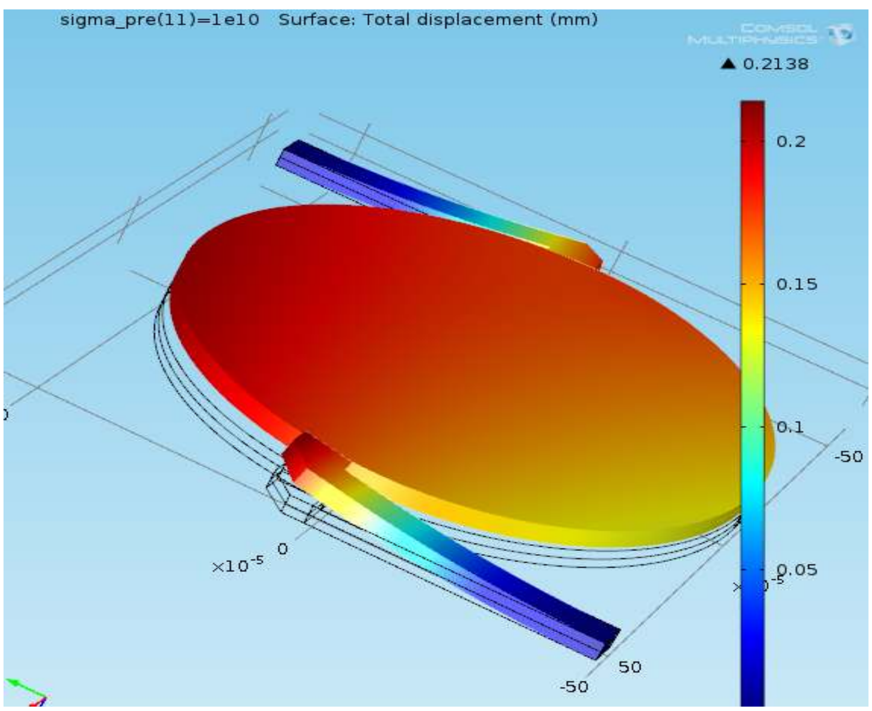

Fig. 8: Simulation using COMSOL-for silicon and structural steel-circular shape

Steel. The distance between the electrodes and the mirror is very close in all the square shapes. They will require very less starting voltage as compared to the others. The Same result can be seen in the figures, which were obtained by simulating the models in COMSOL.

Models of the simulation are shown in Fig. 1 to 9.

Derivation of the pull in effect observed in a micromirror using dynamic equations of a micromirror:

Dynamic equation of a micromirror: Figure 10 shows a conventional micromirror configuration. Firstly, an analytical model of the micromirror is derived for better understanding of the relationship

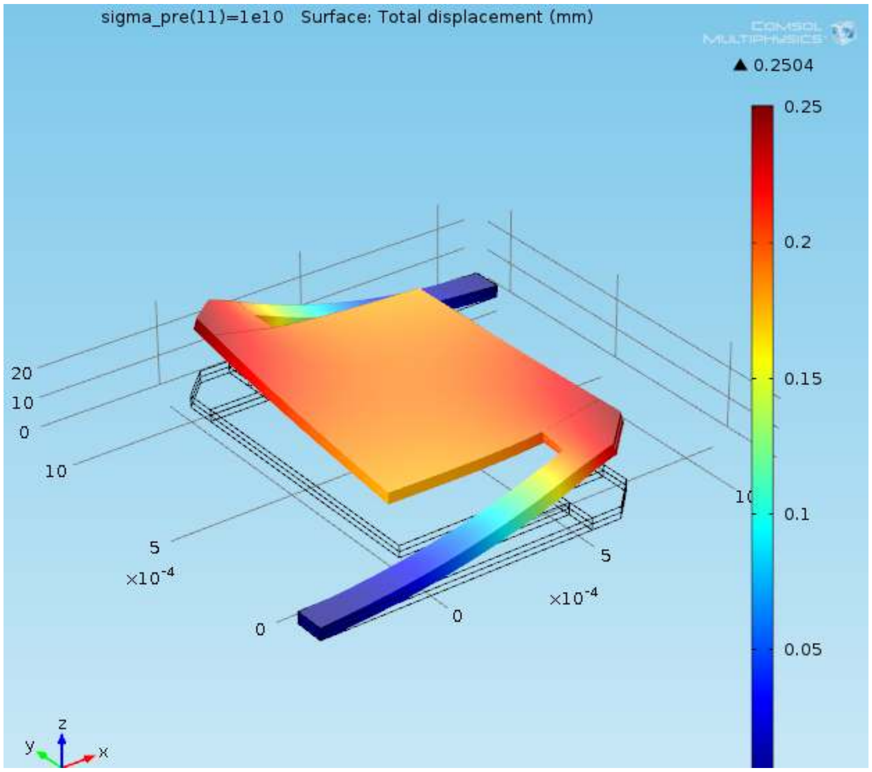

Fig. 9: Simulation using COMSOL-for silicon and structural steel-rectangular shape

Table 2: Total displacement for various shapes of a micromirror

For 2 cantelever legs

Material of the micromirror	Material for the cantelever	Shape of the micromirror	Displacement (mm)
Aluminum	Stainless steel	Square	0.2848
		Circular	0.3032
		Rectangle	0.2621
Copper	Stainless steel	Square	0.2654
		Circular	0.2606
		Rectangle	0.2451
Silicon	Stainless steel	Square	0.2711
		Circular	0.2138
		Rectangle	0.2504

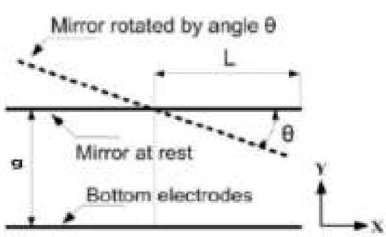

Fig. 10: A conventional micromirror (Bansal and Singh, 2014)

between each parameter of the micromirror. The torque created by the electrostatic force between the micromirror and its electrodes, as denoted by M for each configuration, is derived from the analysis (1).

Using the parallel plate model of Hornbeck, expressions for capacitance and Torque are obtained and are given by:

$$C = \frac{\varepsilon A(x)}{g(x)} = \int_0^L \frac{\varepsilon w}{g - x\sin(\theta)}dx = -\frac{\varepsilon w}{\sin(\theta)}\ln\left(\frac{g - L\sin(\theta)}{g}\right) \quad (1)$$

$$M_e = \frac{\partial U}{\partial \theta} = \frac{\partial}{\partial \theta}\left\{\frac{1}{2}\varepsilon V^2 \int_0^L \frac{w}{g - x\sin(\theta)}dx\right\} = \frac{1}{2}\varepsilon V^2\left(\int_0^L \frac{\partial}{\partial \theta}\left(\frac{w}{g - x\sin(\theta)}\right)dx\right) = \frac{1}{2}\varepsilon w V^2 \int_0^L \frac{x\cos(\theta)}{(g - x\sin(\theta))^2}dx = \frac{1}{2}\varepsilon w V^2 \frac{\cos(\theta)}{\sin(\theta)^2}\left[\ln\left(\frac{g - L\sin(\theta)}{g}\right) + \frac{g}{g - L\sin(\theta)} - 1\right] \quad (2)$$

where,

- L = Equal to the half length of the micromirror
- w = The width of the micromirror
- b = The ratio of the width to the length of the micromirror
- g (or D) = The initial air gap between the micromirror and its electrodes
- ε = The permittivity of air
- Θ = The tilting angle
- V = The potential difference between the micromirror and its electrode

Equilibrium only occurs in a given range. Beyond this limit, the electrostatic force overcomes the spring force causing the two plates to quickly snap into contact. This is known as the pull-in effect. It can be derived as follows:

Total potential Energy $U = U_{me} + U_{es}$.

where,

U_{me} = Strain energy in two torsional strings

U_{es} = Electrostatic energy

Hence:

$$U = 2\times\frac{1}{2}k\theta^2 + \frac{EwV^2}{2}\int_0^L \frac{dx}{D - x\sin\theta} \tag{3}$$

Let:

$$I = \int_0^L \frac{dx}{D - x\sin\theta} \tag{4}$$

Using conditions: When x = 0, m = D, x = 1, m = D-Lsinθ.

Hence from limit D to D-Lsinθ, expression for I in Eq. (4) can be relooked as:

$$I = -\frac{1}{\sin\theta}\ln(D - L\sin\theta) \tag{5}$$

Putting this value in Eq. (3), we get:

$$U = k\theta^2 - \frac{EwV^2}{2\sin\theta}\ln(D - L\sin\theta) \tag{6}$$

Using the value of $\theta = \varphi\,(D^2 / L^2)$.
Therefore Eq. (6) changes to:

$$U = \frac{k\varphi^2 D^2}{L^2} - \frac{EwV^2 L}{2\varphi D}\ln(1-\varphi) \tag{7}$$

At equilibrium U = o, Hence:

$$\frac{k\varphi^2 D^2}{L^2} = \frac{EwV^2 L}{2\varphi D}\ln(1-\varphi) \tag{8}$$

Pull in voltage obtained:

$$V = \sqrt{\frac{2kD^3}{EwL^3}\varphi^3\ln(1-\varphi)} \tag{9}$$

This expression for pull in voltage in Eq. (9) can be used efficiently for designing a micromirror.

Simulation of capacitance and torque using COMSOL: The model was created uses 3D structural analysis using COMSOL software. Electrostatics was used to design the Micro mirror. The parameters used to obtain the models are shown in Table 3. Air was taken as the surrounding material in order to calculate Capacitance. Terminal and ground voltage was applied on different parts of the plates. Force Calculation used on the two edges of the plate to obtain the torque. The final comparison of the simulated and calculated values of a capacitances and torques for all the three shapes has been shown in Table 4.

Table 3: Parameters used to simulate the values of capacitance and torque

Parameters	Square			Rectangle			Circle		
L/2/d/2 µm	0.5	0.5	0.5	0.4	0.4	0.4	0.5	0.5	0.5
sin θ	0.2821	0.1731	0.0572	0.0528	0.1746	0.0933	0.2606	1.0292	1.0480
g (x) mm	0.2848	0.2654	0.2711	0.2621	0.2451	0.2504	0.3032	0.2606	0.2138
θ	16.4000	10.0000	3.3000	3.0000	10.1000	5.4000	15.0000	1.7000	2.8000

Table 4: Comparison between theoretical and practical values for capacitance and torque obtained

Shape	Material of micromirror	Practical value of capacitance µF	Calculated value of capacitance µF	Practical value of torque Nm	Calculated value of torque Nm
Square	Al	2.2343×10^{-7}	2.41×10^{-7}	8.9598×10^{-15}	9.01×10^{-15}
	Cu	2.2237×10^{-7}	2.32×10^{-7}	9.0333×10^{-15}	8.92×10^{-15}
	Si	2.2127×10^{-7}	2.13×10^{-7}	9.1343×10^{-15}	9.63×10^{-15}
Rectangle	Al	1.4046×10^{-7}	1.38×10^{-7}	5.6554×10^{-15}	6.45×10^{-15}
	Cu	1.4421×10^{-6}	1.45×10^{-6}	5.1542×10^{-14}	4.98×10^{-14}
	Si	1.6442×10^{-6}	1.71×10^{-6}	6.5327×10^{-14}	6.12×10^{-14}
Circle	Al	1.7363×10^{-7}	1.74×10^{-7}	5.0188×10^{-18}	5.28×10^{-18}
	Cu	1.7313×10^{-7}	1.76×10^{-7}	5.0128×10^{-18}	5.18×10^{-18}
	Si	2.0346×10^{-6}	2.01×10^{-6}	1.8310×10^{-17}	2.11×10^{-17}

REQUIRED OUTPUT IN THE FORM OF WAVELENGTH OF LIGHT FOR VARIOUS SHAPES OF THE MICROMIRROR

Design requirements: The wavelength of light passed from the micromirror gives us an idea about the range of light that passes through each of the micromirror. Based on the range of light, the micromirror can be used as per the required application. In order to obtain the output, the model was created using 2D structural analysis of COMSOL Multiphysics software. Electromagnetic waves, Frequency Domain was used to design the Micro mirror. Like before, air is taken as the surrounding material. And the angle of micromirror obtained from the earlier Results is taken.

Models of the simulation: Figure 11 to 19, a range of three wavelengths (nm) is shown which demonstrates the range of light that can pass through that micromirror. The first and the last point is taken by keeping in mind the point where the light scatters or gets absorbed. And the central point shows the wavelength for which light passes without any hassle. The tilting angle for these figures is taken from Table 3.

Considering an example of the combination of Copper in circular shape, if we see its graphical view,

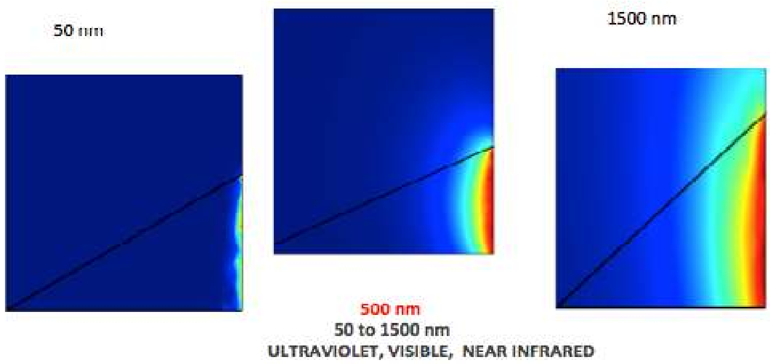

Fig. 11: Range of wavelength passing for aluminum-square-16.4°

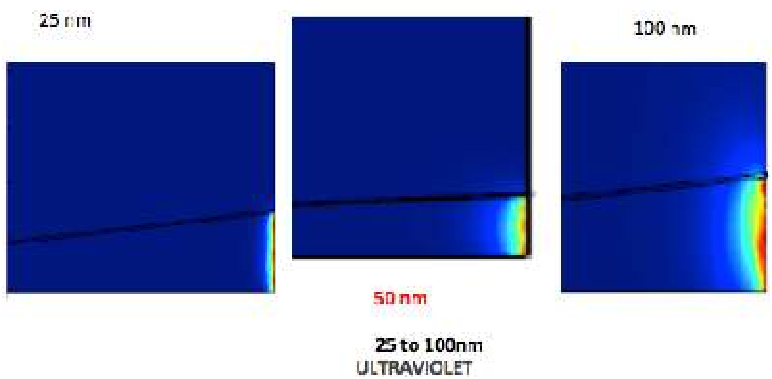

Fig. 12: Range of wavelength passing for aluminum-rectangle-10°

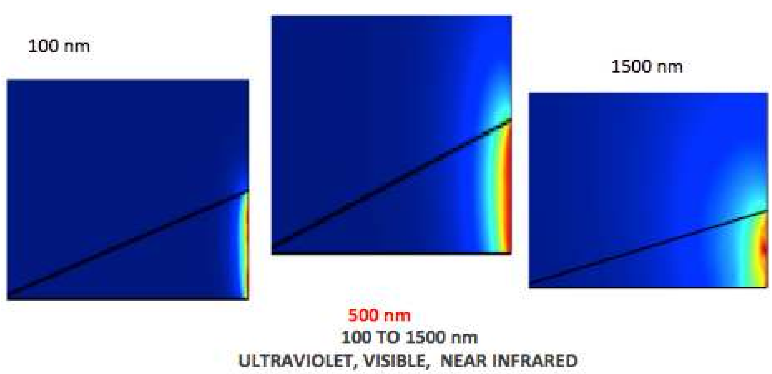

Fig. 13: Range of wavelength passing for aluminum-circle-3.3°

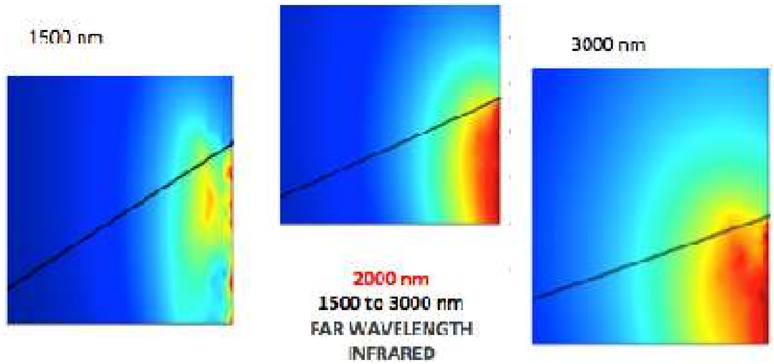

Fig. 14: Range of wavelength passing for silicon-square-15°

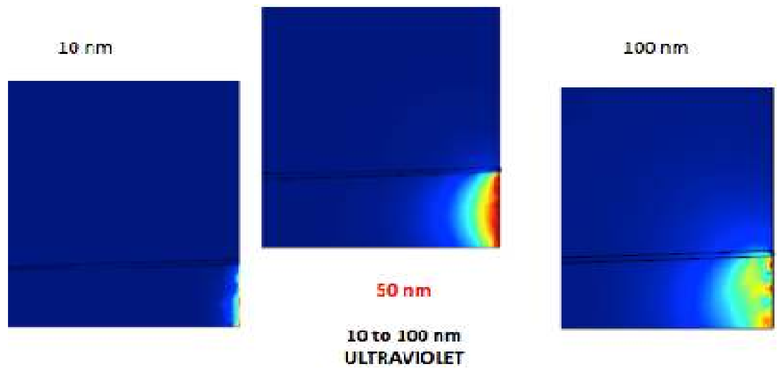

Fig. 15: Range of wavelength passing for silicon-rectangle-1.7°

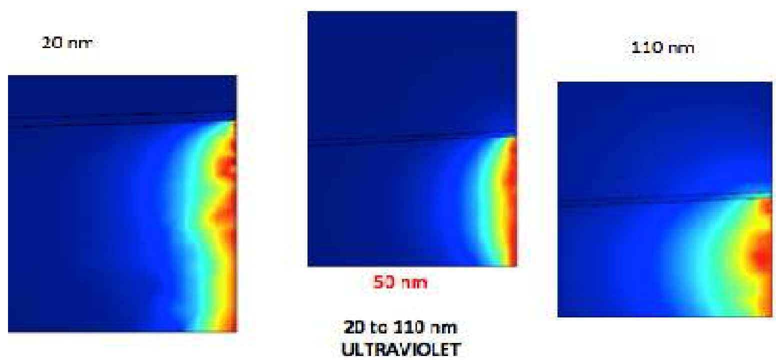

Fig. 16: Range of wavelength passing for silicon-circle-2.8°

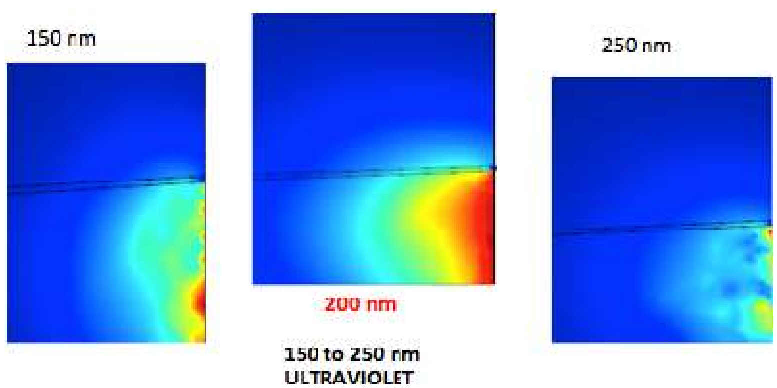

Fig. 17: Range of wavelength passing for copper-square-3°

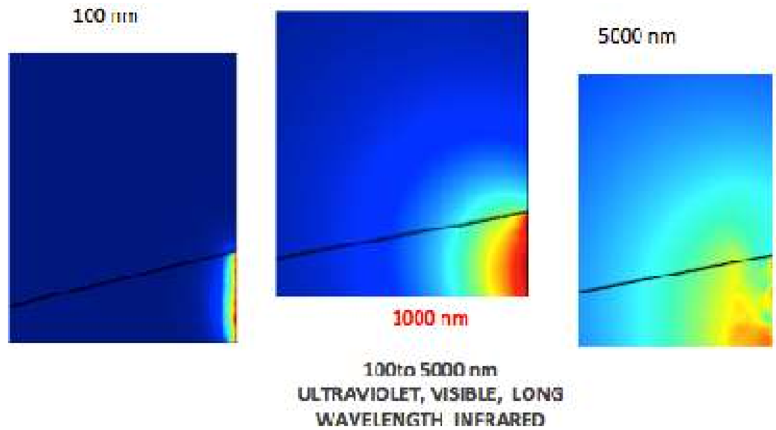

Fig. 18: Range of wavelength passing for copper-rectangle-10.1°

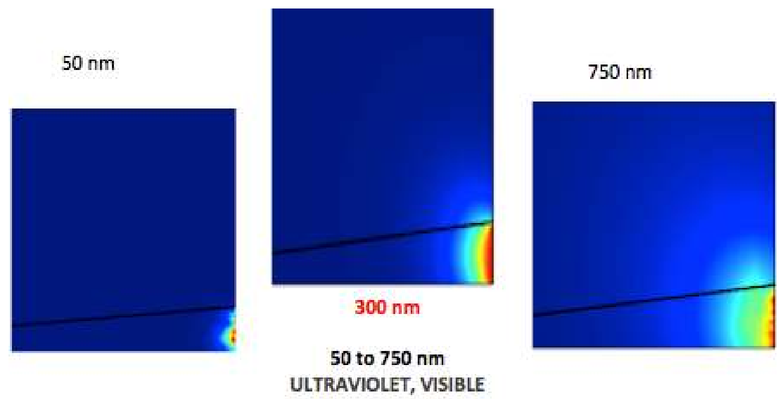

Fig. 19: Range of wavelength passing for copper-circle-5.4°

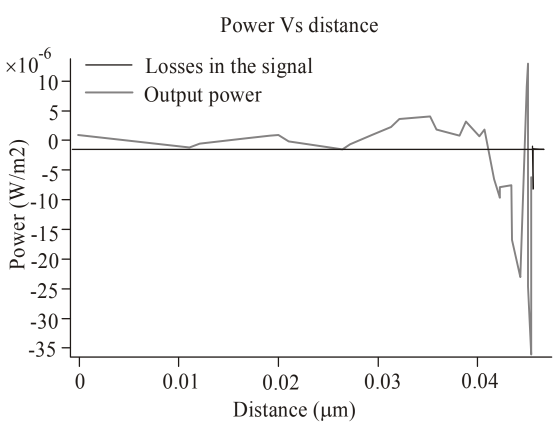

Fig. 20: Copper-circular shape for 50 nm

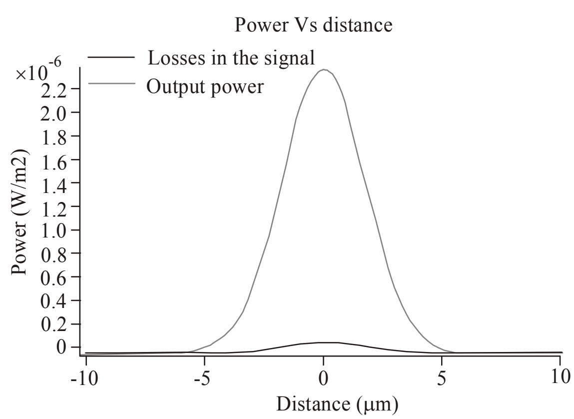

Fig. 21: Copper-circular shape for 300 nm

we can note that the for Fig. 20 to 22, the output is a scattered graph with an uneven display while for Fig. 21 the result is displayed in a rather proper manner.

CONCLUSION

In this study, after a survey of various aspects related to a micromirror, it can be concluded that the combination of Aluminum and Structural steel suffers from high deformation and stress for all the three shapes used and the least displacement is obtained by the combination of Silicon and Structural Steel. Out of all the three shapes studied, the capacitance and torque for Aluminum+Structural steel is highest and the least is obtained or of Silicon and Structural Steel which justifies the first conclusion. Also it has been noticed that the capacitance and torque are seen to be high generally for all the square shapes. From the range of

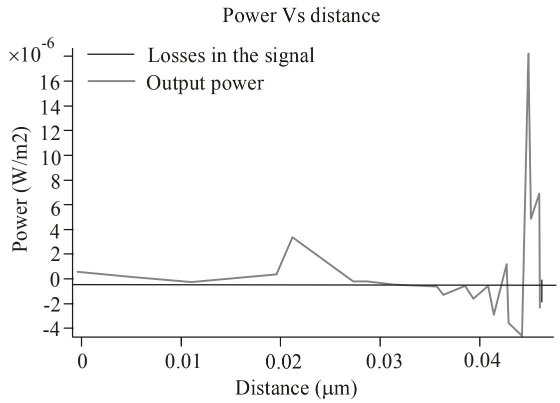

Fig. 22: Copper-circular shape for 750 nm

wavelengths obtained the best shapes and materials, which are used to pass a vast range of light, are Aluminum-Square, Aluminum-Rectangle, Copper-Rectangle. In conclusion, it can be said that the results related to the combination of Aluminum and Structural steel are more favorable as compared to the other shapes and materials. The square shape of this combination of these materials will yield the best result if used as a Micromirror base.

RECOMMENDATIONS

For further studies, It is suggested to include more number of electrodes and shaped in place of the ones used so as to get a wide range of idea related to this field. Also, the formulation can be done which is related to the error obtained from the wavelength range in order to minimize it. Apart from the capacitance and torque values obtained more research and study can be carried out on various other factors for e.g., the switching time and the closed loop behavior of the device.

REFERENCES

Bansal, P. and A. Singh, 2014. Design and analysis of stress level in elecrostatically controlled micromirror. Prog. Sci. Eng. Res. J., 2: 245-248.

Cuiling, G. and D. Mehrl, 2014. Characterization of the digital micromirror devices. IEEE T. Electron. Dev., 61(12): 4210-4215.

Hornbeck, L.J., 1996. Digital light processing and MEMS: An overview. Proceeding of IEEE/LEOS 1996 Summer Topical Meetings: Advanced Applications of Lasers in Materials Processing/Broadband Optical Networks/Smart Pixels/Optical MEMs and Their Applications, pp: 7-8.

Katal, G., N. Tyagi and A. Joshi, 2013. Digital light processing and its future applications. Int. J. Sci. Res. Publ., 3(4), ISSN 2250-3153.

Mamat, H., A.A. Hamzah, A. Jalar, J. Yunas and N.A. Rahim, 2013. A COMSOL model to analyse the structural mechanical problem in an electrostatically controlled prestressed micro-mirror. World Appl. Sci. J., 26(7): 950-956.

Park, S., S.R. Chung and J.T.W. Yeow, 2008. A design analysis of a micromirrors in a stacked configuration with moving electrodes. Int. J. Smart Sens. Intell. Syst., 1(2): 480-497.

Park, S., S.R. Chung and J.T.W. Yeow, 2010. Design and analysis of stacked micromirrors. Excerpt from the Proceedings of the COMSOL Conference 2008 Boston.

Shahid, W., Z. Qiu, X. Duan, H. Li, T.D. Wang and K.R. Oldham, 2014. Modeling and simulation of a parametrically resonant micromirror with duty-cycled excitation. J. Microelectromech. S., 23(6): 1440-1453.

Solgaard, O., A.A. Godil, R.T. Howe, L.P. Lee, Y.A. Peter and H. Zappe, 2014. Optical MEMS: From micromirrors to complex systems. J. Microelectromech. S., 23(3): 517-538.

Van Kessel, P.F., L.J. Hornbeck, R.E. Meier and M.R. Douglass, 2011. A MEMS-based projection display. P. IEEE, 86: 1687-1704.

Wei-Hsin, G., C. Kun-Nan and C. Tao-Ching, 2008a. Measurements and simulation of the dynamic characteristics of micro-machined torsion mirrors. Proceeding of the 3rd International Microsystems, Packaging, Assembly and Circuits Technology Conference (IMPACT, 2008), pp: 145-148.

Wei-Hsin, G., C. Tao-Ching and H. Shin-Chun, 2008b. Examine the design of the micro torsion mirror using holographic and stroboscopic interferometries. Proceeding of 3rd IEEE International Conference on Nano/Micro Engineered and Molecular Systems.