Experimental Set-Up Design and Photostriction Effect Measurement Technique Learning of Photostrictive Optical Actuators

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Abstract

Micro-Electro-Mechanical-Systems (MEMS) become an emerging technology which allows the integration of micromachined mechanical structures with integrated circuits (IC); this has been a vastly growing area of research and technology during the last two decades. MEMS functional elements are sensors, actuators and miniaturized structures. Photostrictive materials are one of the promising areas of research as an advanced optical actuator for MEMS applications. Photostriction is a phenomenon in which strain is induced in the photostrictive materials due to illumination of high intensity light. Photostrictive effect is a superposition effect of the photovoltaic and converse-piezoelectric effects. Incident light generates a large photovoltage due to the photovoltaic effect, and an induced large voltage produces strain due to the converse-piezoelectric effect on the photostrictive materials. Lanthanum modified lead zirconate titanate (Pb, La) (Zr, Ti) O_3 ceramic doped with WO_3, called PLZT, is one of the photostrictive ceramics which has an advantage to use as a wireless remote control over traditional actuators. In this research work an experimental test set-up has been designed and developed for the photostrictive effect measurement of a thin PLZT film on a silicon wafer. The transverse deflection of the PLZT optical actuator cantilever beam has been measured for stationary continuous light as well as for pulses of light using an optical chopper at various light intensities and focused locations. This experimental technique learning can be utilized in the MEMS research for MEMS devices fabrication and application. This technique is also very important in the advancement of actuator and sensor technology.

Keywords

Photostriction, Optical actuator, PLZT, MEMS, and high intensity light.

Introduction

Photostriction is a phenomenon in which strain is induced in photostrictive materials by incident light. In principle, this effect arises from a superposition of the photovoltaic effect, i.e., the generation of large voltage from the irradiation of light, and the converse piezoelectric effect, i.e., expansion or contraction under the voltage applied. A ‘bulk photovoltaic effect’ is noticeable in some ferroelectric (or non-centrosymmetric) materials, such as ferroelectric single crystals or polarized ferroelectric ceramics. Along with this photovoltage, the converse piezoelectric effect induces mechanical strain[1]. The combinations of these two effects make these ferroelectric materials candidates for wireless actuator applications, that is, actuators excited by incident light.

Photostrictive ceramics are one of the promising materials for micro-fabrication technologies, which have photovoltaic, piezoelectric and pyroelectric properties. Photostrictive materials offer the potential for development of advanced actuators with many advantages over conventional electro-mechanical actuators, such as non-contact actuation, remote control, and immunity from electric/magnetic disturbances[2]. Many types of micro-fabrication technologies, such as device design, lithography, film formation, and structure and system integration, have been developed[3]. Traditional actuators, like shape memory alloy and piezoelectric materials, have drawbacks for hard-wire connections such as control signal contamination due to external electro-magnetic disturbance. Photostrictive material appears to have potential for less friction and less weight for use in micro-electro mechanical systems (MEMS) due to its ability to use wireless or remote control. Piezoelectric ceramics have been used commercially as actuators in various fields; it requires hard-wire to supply voltage for actuation. On the other hand, photostrictive actuators can directly convert photonic energy to mechanical motion; they need neither electric lead wires nor electric circuits. A photostrictive type of actuator uses pulses of light instead of electric voltages for actuation. One material that possesses a significant photostrictive behavior under illumination by high-energy light is lanthanum-modified lead zirconate titanate (Pb, La) (Zr, Ti) O_3 ceramic doped with WO_3, called PLZT. In PLZT ceramics, UV and visible light have been found to excite free electrons within the crystalline structure that have greater than band-gap voltages; this is characteristic of a photosensitive material[4]. Also, like a typical ferroelectric material, PLZT can be poled to a remnant saturation polarization state, and the polarization can be switched by the application of an electric field. Due to these photosensitive and ferroelectric responses, PLZT ceramics are often called photo-ferroelectric (PFE) materials. Micro-Electro-Mechanical Systems or MEMS technology can be defined as miniaturized mechanical and electro-mechanical elements that are made using micro fabrication techniques. MEMS functional elements are miniaturized structures, sensors, actuators, and microelectronics; the most important elements are the micro-sensors and micro-actuators. Over the last several decades, MEMS researchers have invented a large numbers of micro-sensors with many sensing modalities, including temperature, pressure, inertial forces, chemical species, magnetic fields, optics, etc. Most recently, MEMS researchers have developed optical switches and mirrors to redirect or modulate light beams[5].

Literature Review

Literature Review on Characteristics of the PLZT Ceramics: PLZT compositions are represented as $Pb_{1-x}La_x(Zr_yTi_z)_{1-x/4}O_3$ or PLZT(X/Y/Z), where X=100x, Y=100y and Z=100z. Ferroelectric materials have a wide range of properties depending on composition[3]. The photovoltaic effect was first discovered in $BaTiO_3$ material[6]. P.S. Brody first proposed photostrictive materials as an opto-mechanical actuator which can be used for MEMS devices to convert optical energy to mechanical energy[7, 8]. When ultraviolet (UV) light falls on the materials, it absorbs photons. Absorbed photons energize electrons and holes to move in a non-random manner; as a result, charges started to flow in an external short circuit of PLZT material. Light illuminates from the top and along the thickness of the material in H direction. The photocurrent of PLZT ceramics varies proportionally with light intensity. Photocurrent increases as the thickness of PLZT film decreases, up to a certain limit[9]. The maximum photocurrent is predicted at 33μm thickness for PLZT (3/52/48) ceramic doped with 0.5% WO_3[10]. If film thickness becomes ultra-thin, then the film does not have enough electrons to flow and photocurrent drops because of size effect[9]. Photocurrent of PLZT materials also depends on the wavelength of illuminating light. The maximum photocurrent is observed at 365 nm wavelength of light, which is out of visible light wavelength range[11]. No significant difference in wavelength dependency has been found between impurity-doped or non-doped samples. However, the valence of impurity has a significant effect on the photovoltaic response. Impurity atoms are classified into three categories: acceptors, donors, and remainder. K^{1+}, Na^{1+}, Mg^{2+}, Ba^{2+}, Al^{3+}& Fe^{3+} atoms are in the acceptor group; Bi^{3+}, Y^{3+}, Nb^{5+}, Ta^{5+}& W^{6+} are in the donor group. Photostriction (x_{ph}) can be defined in terms of photovoltaic voltage (E_{ph}) and piezoelectric coefficient (d_{33}) as $x_{ph}=d_{33}E_{ph}$. Impurities-doping has an effect on the piezoelectric coefficient, which improves photostriction[4]. Steady photovoltage and photocurrent generate in non-centrosymmetric ferroelectric material when illumination light has a wavelength corresponding to the absorption edge of the materials[1]. Generated photovoltage is greater than the band-gap energy for some materials. In certain ferroelectric material, photovoltage is about 1kV/cm and current is in the order of nA; with this photovoltage, mechanical strain is produced due to converse piezoelectric effect[4, 10]. Several models have been proposed to describe the photovoltaic effect[10]. Photovoltage depends on both impurities-doping as well as crystal asymmetry.

Literature Review on the Transverse Deflection of the PLZT Cantilever Beam with the Light Intensity: Tonokai et al. experimentally investigated PLZT on an 8mm×2mm×0.05mm Ti wafer at 50mW/cm^2, 150mW/cm^2, 300mW/cm^2 and 450mW/cm^2 UV light intensities; deflections were found 5µm, 11µm, 18µm and 25µm respectively[12]. Liang et al. experimented on a single-layer PLZT at 3mW/cm^2, 6mW/cm^2, 9mW/cm^2, 12mW/cm^2, and displacements were reported 0.31µm, 0.33µm, 0.42m and 0.57µm respectively[13]. Liang et al. developed a bimorph with amplificatory plate to reach deflection 100 times that of a single layer. The bimorph is constructed by reversing the polarization direction of a pair of PLZT unilateral wafers. The upper PLZT wafer develops a positive charge and expands due to UV light irradiation, and the lower PLZT wafer develops a negative charge and contracts at the same time; as a result, the entire bimorph bends downwards. Thakoor et al.[14] reported that two PLZT ceramics wafers bond together to make a bimorph. The size of the bimorph is 20mm×5mm×0.4mm. The maximum deflection was observed 200µm at the tip at 80mW/cm^2. Fukuda et al.[15] experimented on the two pieces of 21mm×5mm×0.2 mm PLZT, glued in the opposite direction of polarization; the maximum deflections were observed 61µm, 58µm and 37µm at 200mW/cm^2, 100mW/cm^2 and 25mW/cm^2 light intensity respectively.

Literature Review on the MEMS Applications: Photostrictive effect of PLZT is useful for MEMS applications because it can serve as a current and voltage source for optical sensors at the same time. However, it requires some improvements: (1) improvement of output current; and (2) improvement of response[16]. Using the electrical properties of PLZT, an optical motor was developed as an electro-mechanical device suitable for miniaturization[3]. The optical motor driving principle was described with stator pads and moving pad. The PLZT electrode is connected with stator pads. When light falls on a PLZT electrode, high voltage generates between the stator and moving pad; then the moving pad starts to move towards the stator side. In an optical motor rotor disk has four pads, and each stator disk has three pads. The rotor disk was fixed or aligned with the motor axis, which is on the bearing. When light falls on PLZT ceramics, high voltage generates in the stator, and the rotor is pulled into the stator in a clockwise direction from the top view. The optical motor could be rotated, but its speed would be very slow.

Internet traffic has grown enormously with the development of broadband access; a PLZT optical actuator could play a significant role in high-speed data transfer systems[17]. PLZT actuators can be used as high speed optical switches benefits including low-voltage, low power consumption, low-polarization independence, noise robustness and switching speed of less than a nano second[18, 19]. Furukawa et al.[20] made a 1×8 PLZT optical switch whose switching speed is less than 2.5ns. Satol et al.[21] developed an 8×8 channel switch comprised of a PLZT deflector, fiber array, micro-lens and slab waveguide. Switching speed was less than 1µs. PLZT bimorphs could also be used as a photo driven relay, consisting of two ceramic plates bond together in opposite polarization direction and a dummy PLZT plate placed adjacent to the bimorph. Switching could be controlled by alternately irradiating light on the bimorph and dummy plates[22]. A micro-walking machine has been developed using photostrictive bimorphs. Two PLZT ceramic legs are fixed on a plastic board; light irradiates on the legs alternately and the micro-walking machine moves like an inchworm at very low speed 10µm/min[23]. An optical gripper was developed using a PLZT bimorph actuator. There are two bimorph actuators and UV light is irradiated by optical fibers on each actuator independently using two mirrors. Displacement of the gripper at the tip was reported 100µm. The gripper has strong anti-noise characteristics and could be used for micro-surgery[15]. A photocurrent generates due to irradiation of light on the photostrictive actuator; this property has been used as an image comparator. One image is stored as a sequence of spatially varying ferroelectric domains. The second image is projected on the first and generates a photocurrent representing the dot product of stored and projected images[24]. Photostrictive materials also can be used as solar tracking shutter and photo phone[13]. Photo generated deflection could be used to walk on the surface or to run a motor indirectly. This kind of wireless optical control of advance mobile vehicle would be used for hazardous, hard to reach location, as long as it is in the range of sight. Scattering effect of PLZT has been used to construct display devices and optical shutters, optical information storage and processing[14, 25].

Research Objectives

Photostrictive actuators have the superiority of remote sensing capability and freedom from external electric/magnetic disturbance, unlike conventional actuators. Based on this inspiration, a PLZT thin film placed on the top of a silicon wafer is used to support a systematic characterization of photostrictive properties to develop an actuator. The main goal of the research is to investigate the potential of the PLZT material as a wireless actuator to convert photonic energy to mechanical energy. The objectives of this research work are: (1) to design and develop an experimental test set-up for the photostrictive effect measurement of a thin PLZT film on a silicon wafer, (2) to study and learn the technique to measure the transverse deflection of the PLZT optical actuator cantilever beam for stationary continuous light as well as for pulses of light using an optical chopper at various light intensities and focused locations, (3) to learn and implement how this experimental technique can be utilized in the MEMS research for MEMS devices fabrication and application, and (4) to study and learn how this technique can advance the actuator and sensor technology.

Methodology

Experimentation has been performed mainly using a high intensity light source, a good repeatability displacement measurement sensor and a photostrictive optical actuator. The goal of the experiment was to observe the transverse deflection of a PLZT thin film on a silicon wafer cantilever beam under the illumination of continuous and pulses of high intensity light.

Experimental Set-up Design and Development: The experimental test set-up was designed to measure the photostriction effect of a photostrictive optical actuator as shown in Figure 1.

The set-up consists of a high pressure short arc xenon lamp with lamp housing, power supply with igniter, hot mirror, band pass filter, optical chopper, photostrictive cantilever type optical actuator, and laser sensor head with controller. Based on the design, an actual experimental set-up was developed as shown in Figure 2.

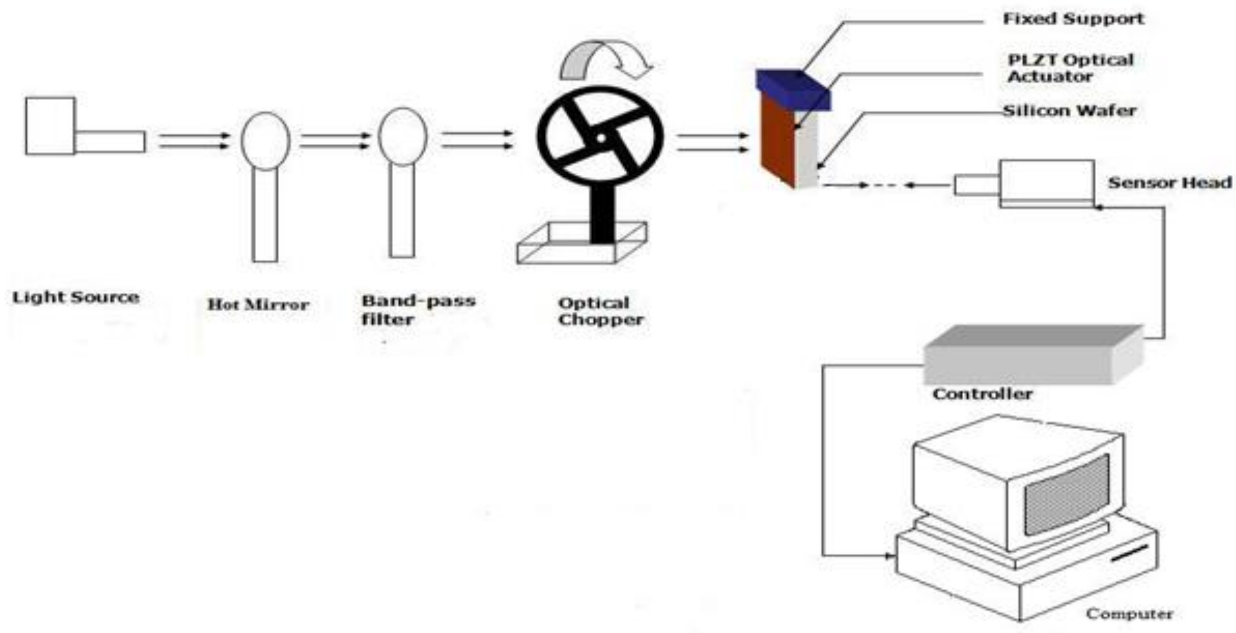


Figure 1: Schematic diagram of the experimental set-up for photostriction effect measurement.

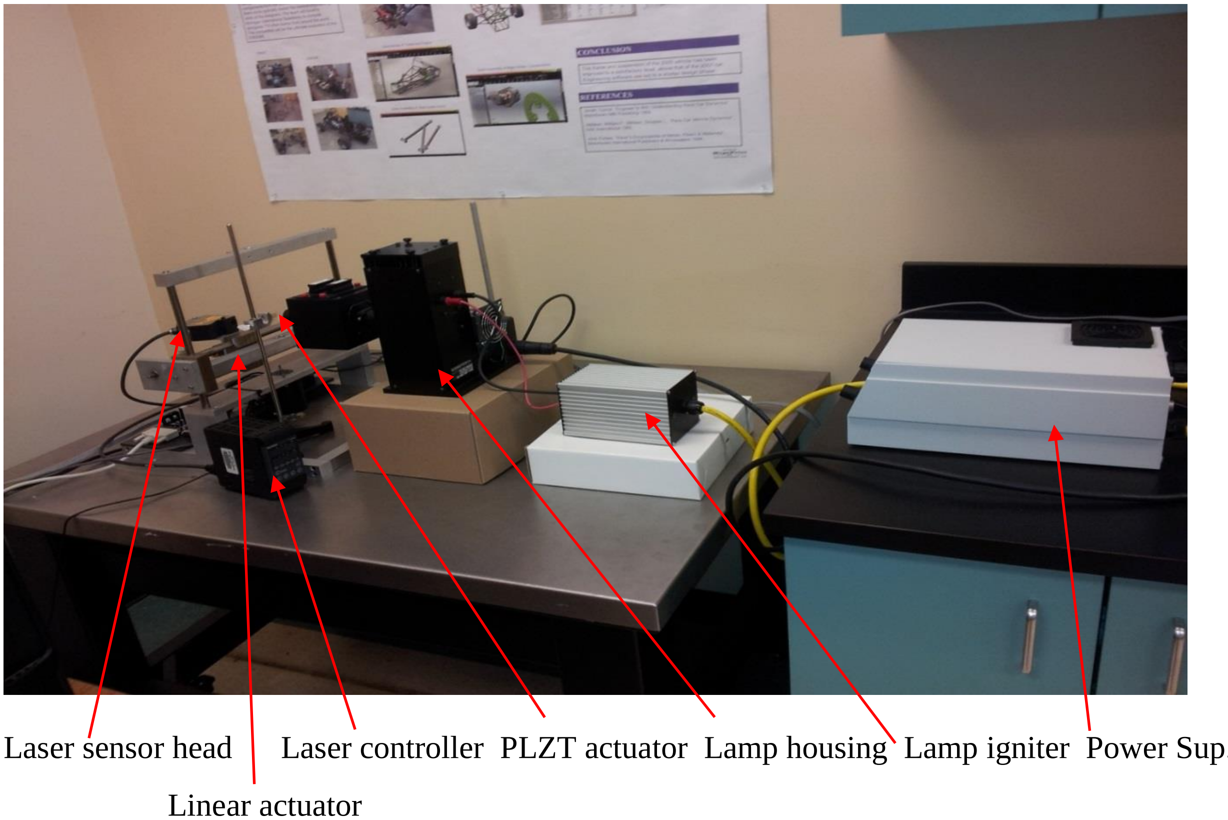
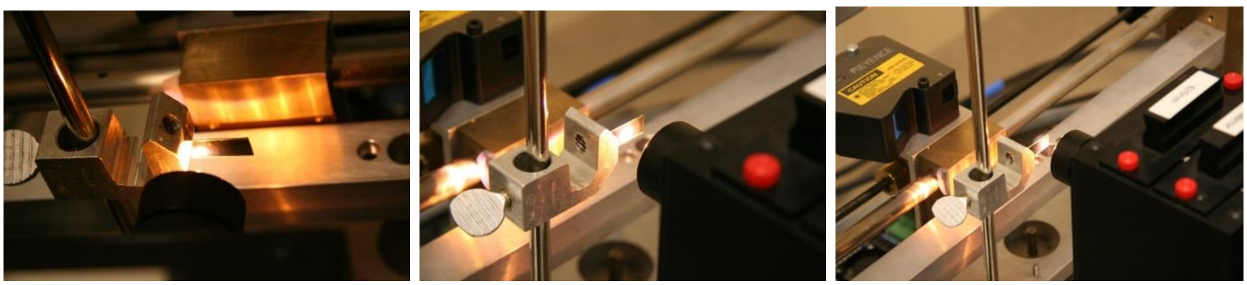


Figure 2: Experiment set-up for transverse deflection measurement of a cantilever beam.

A 150 watt xenon short arc lamp was provided high intensity light for maximum photovoltaic effect on the optical actuator. The arc lamp was placed inside the Science Tech 201-100 series lamp housing. A model 500-200 series AC power supply and a model 500-IG igniter were used to turn on the short arc lamp. To produce pulses of high intensity light on an optical actuator the Scitech 300CD model an optical chopper was used. A Keyence LK-H087 laser sensor head with 0.1 µm repeatability was used to measure the transverse deflection of actuator beam. Laser sensor data acquisition was controlled by the Keyence LK-G5001V model laser sensor controller. The beam deflection data was recorded in the computer through the laser sensor controller and data acquisition system. A heat absorbing glass (also called hot mirror lens) was placed in front of the lamp housing, to absorb high heat which was generated by the arc lamp. A UV band-pass filter was placed behind a heat absorbing filter, which allowed only 428nm wavelength of light to pass. This high intensity UV light went through a lamp housing window lens and was used to produce the photostriction effect on the optical actuator. A diamond cutting blade was used to cut the sample into the desired shape (18mm× 8mm) for the experiment. PLZT thin film on silicon wafer sample was mounted as a cantilever beam on a stand. An LK-H087 laser displacement sensor was mounted on a linear actuator at the other side of the light source. The linear actuator can travel a minimum of 0.1mm/step in the horizontal direction, thus allowing the laser displacement sensor head to move along the length of the sample cantilever beam. To irradiate pulses of light on the sample a variable frequency optical chopper was placed between the sample and the lamp housing window lens. Source light beam has a maximum light intensity of 250mW/cm^2 at its focal point through the lamp housing window lens at 20cm distance which was measured by a UV meter. The UV meter sensor head was 12mm in diameter which measured the intensity on the average of sensor head area.

It was not experimentally possible for the whole cantilever beam to be exposed with equal light intensity. The light intensity starts to decrease as we move away from its focal point on the perpendicular plane. Experiments were performed by focusing the light on the targeted cantilever beam at three different locations; these are the free end, middle and fixed end as shown in Figure 3. Using the UV meter the light intensities measured, at a distance of 20cm, 25cm and 35cm from the lamp housing window lens, were 250mW/cm^2, 200mW/cm^2 and 100mW/cm^2 respectively.



(a) **(b)** **(c)**

Figure 3: UV light was focused (a) at the fixed end, (b) at the middle, and (c) at the free end of the cantilever beam.

Experimental Procedure: In conducting the experiment to produce photostriction effect and measuring the transverse deflection of the actuator, the following steps have been followed:

- A high pressure short arc xenon lamp was placed properly inside the lamp housing with right polarity of cathode (-) and anode (+). This was used as a UV light source for the experiment.
- A power supply and a lamp igniter were connected to the lamp housing; and the lamp housing was placed on a vibration isolation table.
- A hot mirror lens and a 428nm wavelength filter were placed after the lamp inside the housing filter slot. The source light first passed through the hot mirror then through the 428nm wavelength filter.
- Output light was focused on the PLZT optical actuator cantilever beam at different distances from the output lens to get various light intensities on the targeted area.
- A frequency variable optical chopper was placed in between the light output lens and the PLZT cantilever beam to produce pulses of light on the targeted area as shown in Figure 4.
- The laser displacement sensor head was connected with the controller. The controller was powered by a 24VDC adapter. The laser sensor head was placed at the backside of the target which was the opposite side of the light source.
- The controller was connected to the computer by USB port to collect measured data in the personal computer (PC).

- Transverse deflection of the cantilever beam was measured by the laser displacement sensor along the length of the cantilever beam for every 1 mm distance from the free end. All measured data was recorded in the PC.
- Data was collected from the laser sensor 0.1sec intervals. An average of 20-30 seconds of collected data was recorded for analysis as shown in Figure 5.
- During the experiment, the photostrictive optical actuator cantilever beam was exposed for 5 minutes to the high intensity UV light then light was turned off and data was collected for 3 minutes.
- The average of three sets of data was plotted for the analysis.

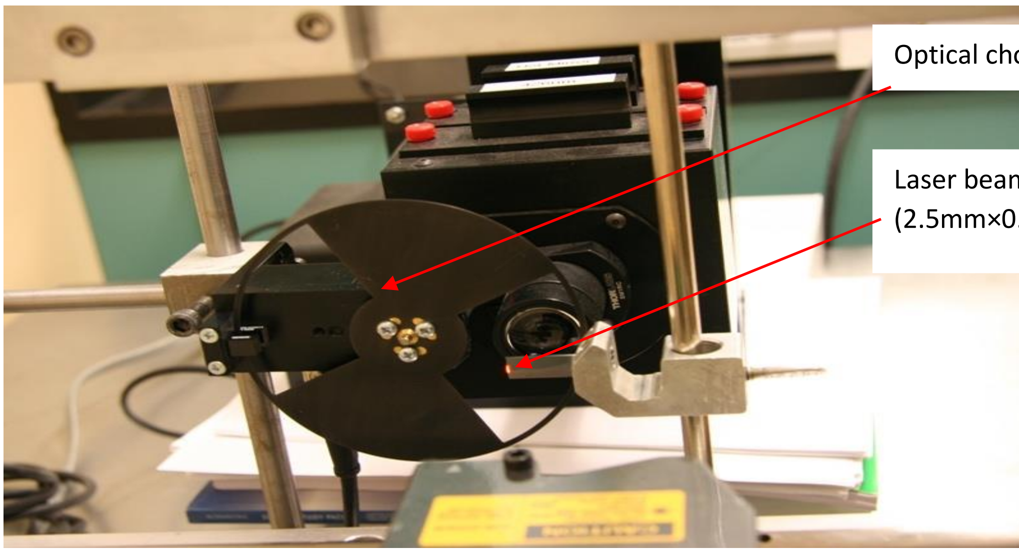


Figure 4: Optical chopper placement in the experiment set up to observe response for the pulses of light.

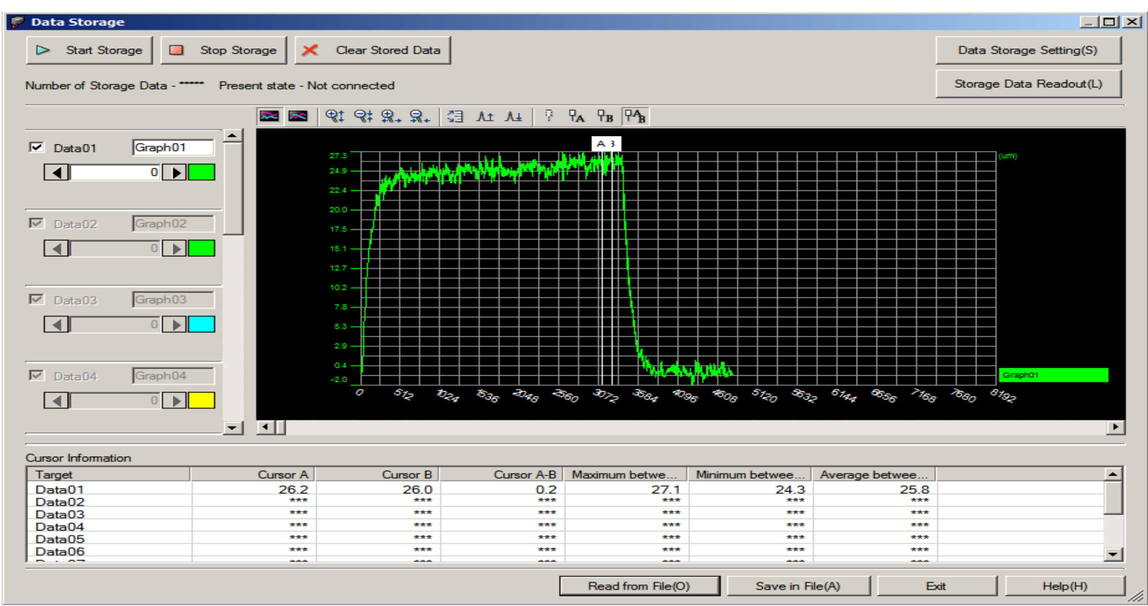


Figure 5: Controller output data collected in every 0.1sec interval for 480sec.

Some Experimental Results Using Photostrictive Effect

A photostrictive optical actuator was exposed under the uniform illumination of UV light for a certain period of time. Transverse deflection of the PLZT optical actuator cantilever beam is analyzed at various light intensities and various focused light positions. Comparison of transverse deflection is also presented.

Dependence of Transverse Deflection on Light Intensity at Specific Light Focused Position: Transverse deflections of the cantilever beam at 250mW/cm^2, 200mW/cm^2 and 100mW/cm^2 light intensities were observed with light focused at different locations on the beam. Data plotted along the length of the cantilever beam are shown in Figures 6, 7 and 8 respectively. Deflections were measured every 1 mm distance along the length of cantilever beam. The negative deflection means the cantilever beam was deflected in the opposite side of light source. From the figures it can be seen that the transverse deflection near the fixed end of the beam was very small; it increased with the increase of distance from the fixed end. And the maximum transverse deflection was observed at free end of the beam. Also, transverse deflection of the beam depends on the light intensity and it increases with the increase of light intensity at each specific focused location of the cantilever beam.

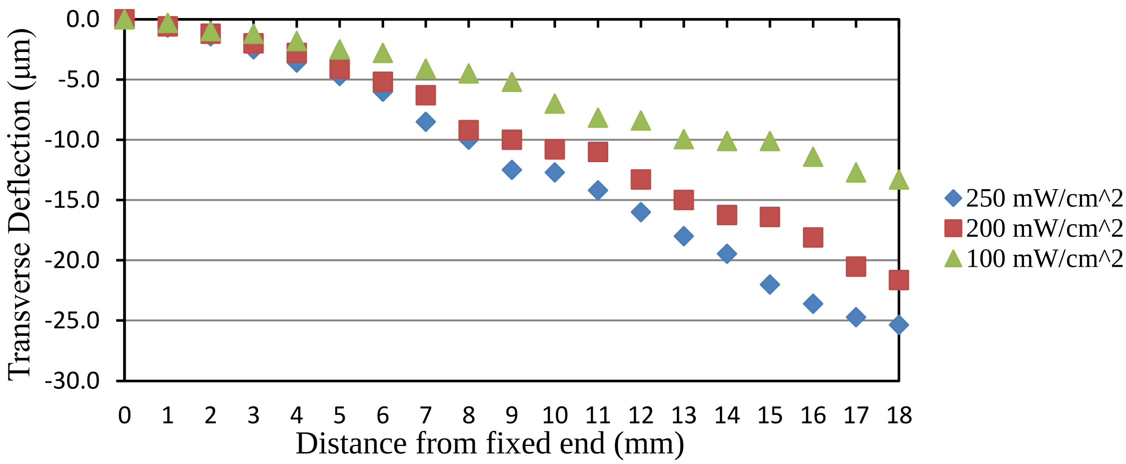


Figure 6: Transverse deflection distribution when light was focused at the fixed end.

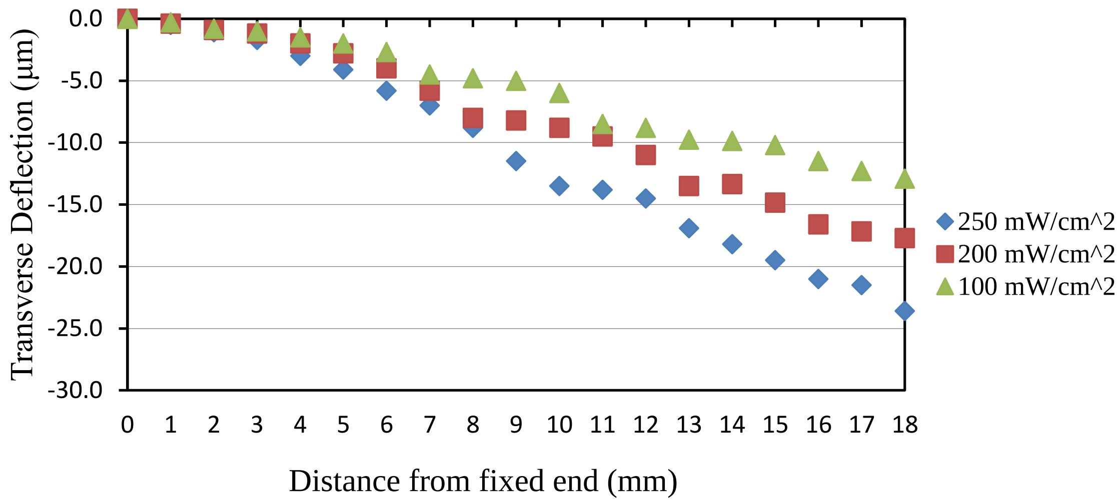


Figure 7: Transverse deflection distribution when light was focused at the middle.

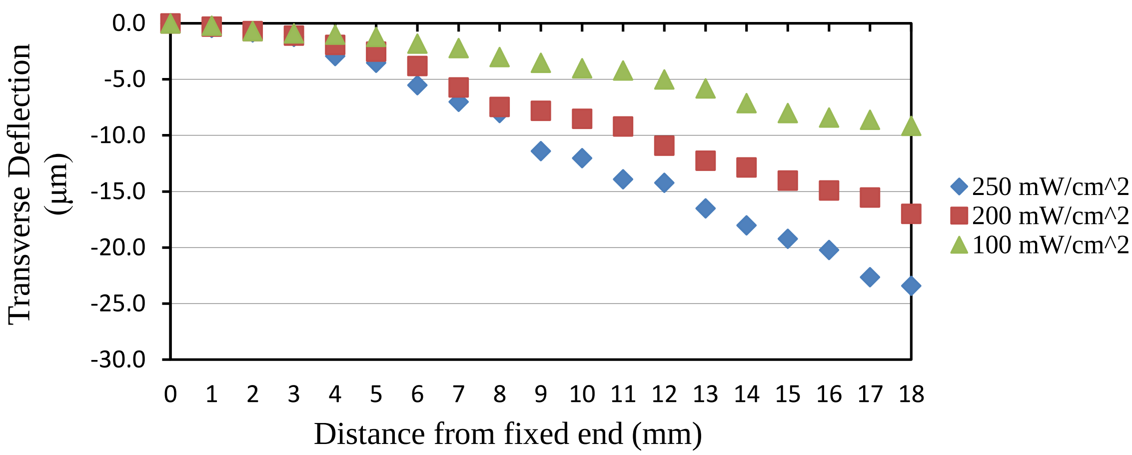


Figure 8: Transverse deflection distribution when light was focused at the free end.

Dependence of Transverse Deflection on Light Focused Position at Specific Light Intensity:
Transverse deflection of the beam also depends on the locations of light focused on the beam. Deflection was the maximum when the light was focused near the fixed end of the beam and it was minimum when the light was focused at the free end. Variation of transverse deflections due to light focused positions variation were observed for three specific light intensities as shown in Figures 9, 10, and 11. Deflections of the beam when the light was focused at the middle and at the free end were almost the same at 250mW/cm^2 as shown in Figure 9. At 200mW/cm^2, when light was focused at the middle, deflection of the beam was more than the deflection when the light is focused at the free end but less than the deflection when the light is focused at fixed end as shown in Figure 10. When the gap between the light source and the targeted area of the beam increases, the light beam diffused and allowed the cantilever beam to expose more light to the actuator surface; this happened especially when the light was focused at the middle position compare to other two positions. At 100mW/cm^2, the deflections were the same when the focused position of the light was at the middle and at the fixed end of the cantilever beam as shown in Figure 11. More diffused light fell on the beam surface when the light was focused at the middle

of the beam compared to other two positions.

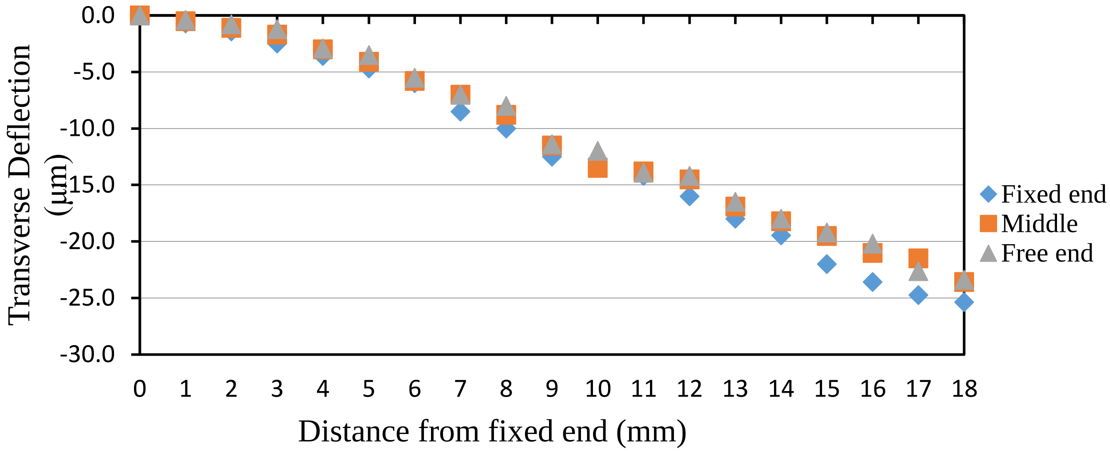


Figure 9: Transverse deflection distribution for three light focus positions at 250mW/cm^2.

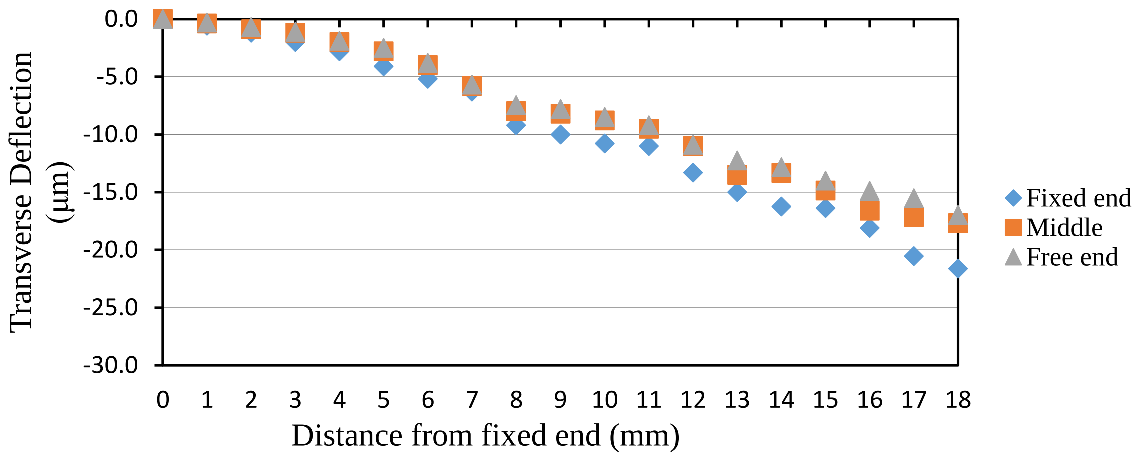


Figure 10: Transverse deflection distribution for three light focus positions at 200mW/cm^2.

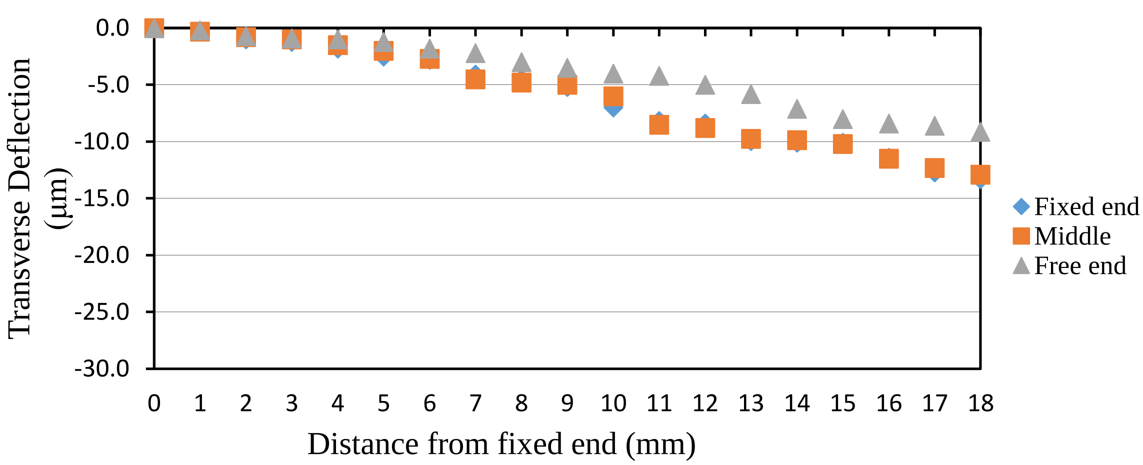


Figure 11. Transverse deflection distribution for three light focus positions at 100mW/cm^2.

Results for the Pulses of Light

Tests were performed by placing an optical chopper in between the PLZT cantilever beam and the UV light source. The PLZT cantilever beam was exposed to illumination of pulses of light intermittently by the optical chopper. The two slot blade optical chopper was run with a frequency of 0.5HZ which allow the beam be exposed to illuminations of light for 1sec on and 1sec off. The experiment was conducted at the light intensities of 250mW/cm^2, 200mW/cm^2 and 100mW/cm^2. In these pulses of light case, light was focused only at the middle of the cantilever beam.

Comparison of Transverse Deflection with the Light Intensity**:** It has been observed that the magnitude of the corresponding transverse deflection along the length of the cantilever beam decreases in the pulses of light condition in comparison to the continuous light condition. Transverse deflection increases along the length of the actuator beam with the increase of distance from the fixed end as shown in Figure 12. Also it has been observed that the deflection of the cantilever beam increases with increase of the light intensity.

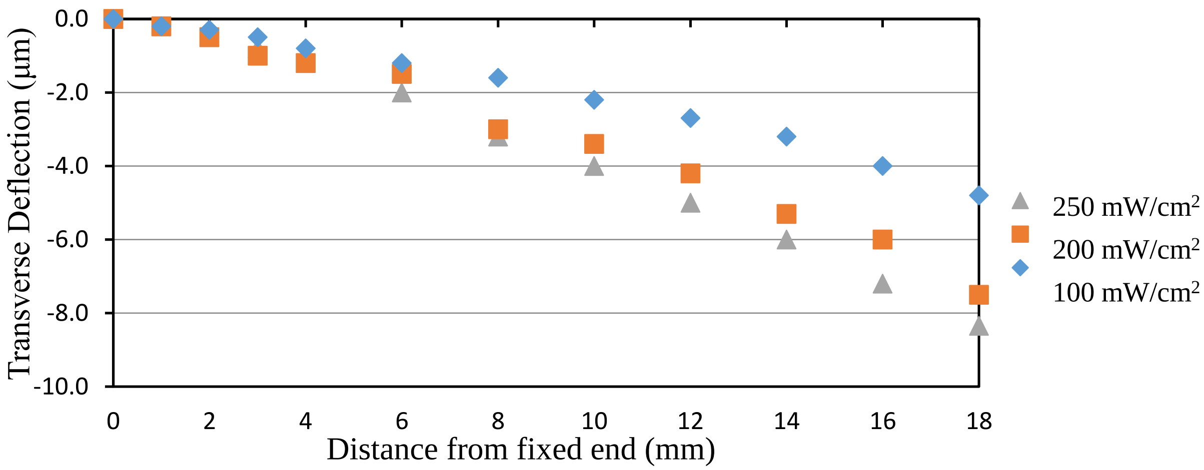


Figure 12. Transverse deflection at three different light intensities for pulses of light condition.

Conclusions

From this experimental investigation, it has been observed that the continuous and pulses of lights have a significant influence on the transverse deflection of PLZT optical actuator; less deflection was observed for the pulses of light compare to the continuous light. The PLZT optical actuator could be used in the MEMS applications as a wireless control but the time response of the actuator was observed slow. The light intensity and focused locations of the cantilever beam have no influence on the time response. Rising time was observed about 20sec to reach 63% of the steady state the maximum deflection for both continuous and pulses of light conditions. Deflection of the cantilever beam was approaching to steady state after about 180sec for both continuous and pulses of lights.

From the current study, analysis and results of this research, the following conclusion can be made: (i) Experimental transverse deflection of cantilever beam increases with the increase of light intensity for both continuous and pulses of lights. (ii) Maximum tip deflection at the free end of the cantilever beam for pulses of light was less than that for continuous light.

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