A 2-D MEMS scanning mirror based on dynamic mixed mode excitation of a piezoelectric **PZT thin film S-shaped actuator**

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Abstract: A novel dynamic excitation of an S-shaped PZT piezoelectric actuator, which is conceptualized by having two superimposed AC voltages, is characterized in this paper through the evaluation of the 2-D scanning characteristics of an integrated silicon micromirror. The device is micromachined from a SOI wafer with a 5µm thick Si device layer and multilayers of Pt/Ti/PZT//Pt/Ti deposited as electrode and actuation materials. A large mirror (1.65mm x 2mm) and an S-shaped PZT actuator are formed after the backside release process. Three modes of operation are investigated: bending, torsional and mixed. The resonant frequencies obtained for bending and torsional modes are 27Hz and 70Hz respectively. The maximum measured optical deflection angles obtained at $3V_{pp}$ are \pm 38.9° and $\pm 2.1^{\circ}$ respectively for bending and torsional modes. Various 2-D Lissajous patterns are demonstrated by superimposing two ac sinusoidal electrical signals of different frequencies (27Hz and 70Hz) into one signal to be used to actuate the mirror.

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1. Introduction

Optical microelectromechanical systems (optical MEMS) technology has demonstrated enormous promises in numerous key commercial applications [1-4]. The integration of micromechanical parts and CMOS circuits have facilitated mass production of MEMS devices in CMOS foundries due to the well-established quality control system in production line, low fabrication cost, and proven successful foundry-design house business model, etc. However, limited material selection in CMOS manufacturing line and CMOS compatible processes restrict the Si-based actuators to be mainly electrostatic or electrothermal [5,6]. Exploring new actuation mechanisms from the standpoints of optical MEMS mirror operation remains as challenging tasks when we consider various key features such as achieving larger deflection angle in a smaller device footprint with a lower driving voltage, and achieving 2-D raster scanning patterns by optimized actuation mechanism and mirror structures.

Besides the difference in actuation mechanisms, a wide variety of 2-D scanning mirror designs have also been reported in literature, with most of them deploying either the two frames or/and multi-actuators design for 2-D actuation [7-10]. Each frame or set of actuators is responsible for its individual scanning axis, hence essentially making horizontal and vertical scanning to be two decoupled actuation mechanisms respectively. Such decoupled actuation mechanisms using different integrated structures for 2-D scanning make designing of 2-D scanning mirror fairly straightforward as actuation mechanisms for both scanning axes are almost independent of each other. It remains a technically demanding feat to design 2-D

scanning mirrors using only single actuator structure due to the constraint of the scanning effects of both axes being coupled together. Nonetheless, a straight cantilever mirror design has been made by O. Isikman *et al.*, where magnetic permalloy NiFe was electrodeposited on a mirror plate supported by a straight, narrow cantilever beam [11]. This single cantilever actuated mirror allows for 2-D scanning by using superimposed ac currents corresponding to the frequency of bending and torsional mode to excite the external electro-coil. Various gimbaled electromagnetic actuated 2-D scanning mirrors using the same actuation mechanism i.e. superimposed current carrying different excitation frequencies were also reported previously [7,10]. However, such electromagnetic actuated 2-D MEMS scanning mirrors require the presence of either an external permanent magnet or electromagnetic, resulting in bulky packaging.

On the other hand, piezoelectric PZT (PbZr_xTi_{1-x}O₃) films have reported as sensors and actuators for various applications because of their potential to offer higher output force at lower voltage compared to the other actuators [12–14]. By leveraging the unique piezoelectric effect, a PZT microcantilever with self-exciting, sensing and actuation capability has been conceptualized for atomic force microscopy [13,14]. This kind of smart functions originating from piezoelectric effect renders us a room for creating new designs of piezoelectric 2-D scanning mirrors, which help eliminates the issue of scalability and high input voltage in electromagnetic and electrostatic actuated 2-D mirror respectively.

F. Filhol *et al.* realized a piezoelectric driven torsional micromirror for 1-D scanning based on 0.5μ m PZT thin film actuation, with an achieved total optical deflection angle (ODA) i.e. 40, of 78° at less than $1V_{pp}$ in vacuum condition [15]. A large elliptical 2-D micromirror (1mm x 2mm) driven by 3μ m PZT thin film was demonstrated by Y. Yasuda *et al.* [16,17]. Two orthogonal pairs of ring-actuators were used to compose a double-gimbal structure, allowing the mirror to obtain an ODA as large as 23° (4.3kHz for X-scan) by 52° (90.3Hz for Y-scan) at driving voltage of typical 10-20V_{ac} with a $5V_{dc}$ offset. Additionally M. Tani *et al.* adopted multiple meandering actuators in both inner and outer frames so as to accumulate angular displacement and generate large static deflection angle [18, 19]. 2-D scanning was made possible by combining resonant motion for the fast horizontal axis at 11.2kHz with an ODA of 39° and quasi-static operation for the slow vertical axis at 60Hz with an ODA of 29° [18], while the ODA for both axes were obtained at $40V_{pp}$ ac voltage. By using separate patterns of PZT thin film on a torsional micromirror, Kobayashi *et al.* reported the integration of more functions including ac actuation for 1-D scanning, displacement sensing and dc actuation for resonant frequency tunning [20]

Two superimposed ac excitation biases, which have already been performed on resistive type electromagnetic coils [7,10,11], are yet to be examined on capacitive type piezoelectric actuator. In addition, there are still limited research efforts being made on simple MEMS mirror design that utilizes only a single actuator to achieve 2-D scanning effect, as compared to those reported activities in two frames, multi-actuators driven mirror. Hence, our motivation here is to explore a novel 2-D actuation mechanism that has not been reported previously on a piezoelectric actuator and integrate it with a silicon micromirror for 2-D optical scanning illustration. By demonstrating a proof-of-concept 2-D scanning mirror, the superimposition of two ac excitation biases on a single piezoelectric actuator during dynamic mixed mode actuation is realized and characterized in this study.

2. Design and modeling

Piezoelectric actuator made of a number of bars of PZT electrically connected in parallel and mechanically connected together in series in a meander line configuration was first conceptualized by W. P. Robbins *et al.* in 1991 [21], in which experimental data on in-plane actuator displacement were collected. Such meandering PZT actuator design was not incorporated into MEMS mirror till the works done by M. Tani *et al.* in 2005, as mentioned previously [18,19]. Such meandering design offers benefits such as smaller footprint, larger displacement due to lower mechanical stiffness and expanding the area of PZT fabrication hence increasing actuation force. By leveraging such advantages, a S-shaped PZT actuator

integrated with a MEMS 2-D scanning mirror is proposed as shown in Fig. 1(a). The detailed dimensions of the device are given in Fig. 1(b) and summarized in Table 1. The mirror plate is driven by a S-shaped PZT actuator, which is capable of 6 degrees of freedom of movement. The actuator main composition consists of a top electrode layer (Pt/Ti), a piezoelectric thin film (PZT) and a bottom electrode layer (Pt/Ti). The top and bottom electrodes are each connected to their individual bond pads. A proof mass is left beneath the mirror to maintain the rigidity and flatness of the reflecting surface during motion. Bending mode occurs in both static and dynamic actuations. When an ac or dc bias is applied to the piezoelectric actuator, the actuator bends and causes the mirror to undergo translational and rotational movement along the y-axis. Torsional mode is induced during dynamic actuation, when ac resonant frequency corresponding to rotational motion along x-axis is applied to the device.



Fig. 1. (a) Schematic drawing of 2-D scanning mirror actuated by S-shaped PZT actuator. Bending and torsional mode occur when the device is excited at their resonant frequencies respectively. (b) Top view of mirror device and the respective dimensions of the structures.

Table 1. DIMENSIONS of 2-D MEMS Scanning Mirror

Chip	Si mirror plate	S-shaped PZT actuator
5.2mm x 4.2mm	1.65mm long x 2mm wide x 0.4mm thick	Longitudinal (x-direction): 1.6mm Transverse (y-direction): 3.6mm Thickness (z-direction): 9.2µm Total length: 5.2mm

To better understand the operation modes, finite element analysis was done using the software ABAQUS. As shown in Fig. 2, two designs were simulated: S-shaped design and straight beam actuator design. The actuators in both designs have the same thickness (9.2µm), width (0.2mm), longitudinal length (1.6mm) and mirror plate dimensions for fair comparison. Both designs were assumed to be made entirely of silicon. The input parameters for silicon were poisson ratio (0.3), mass density (2330kg/m³) and Young's modulus (160GPa). A homogenous solid with isotropic elasticity was chosen. An encastre boundary condition was implemented on the fixed end of the actuator. Figure 2(a) and 2(b) show the S-shaped design during bending and torsional mode respectively, while Fig. 2(c) and 2(d) show the straight beam actuator design during bending and torsional mode respectively. During bending mode operation simulated in Fig. 2(a) and 2(c), both designs show very similar results in terms of resonant frequency and maximum Z-displacement. Resonant frequencies of 34.9Hz and 35.3Hz were obtained for S-shaped and straight actuator beam designs respectively. Both designs obtained the same maximum out-of-plane or Z-displacement. However, during torsional mode operation simulated in Fig. 2(b) and 2(d), the results obtained for both designs were significantly different. Resonant frequencies of 72.1Hz and 128Hz were obtained for Sshaped and straight actuator beam designs respectively. In addition, the maximum Zdisplacement obtained was larger in the S-shaped design compared to the straight cantilever design. This can be explained by the lower mechanical stiffness of the S-shaped actuator

compared to the straight one, hence causing the resonant frequency to be lower and Zdisplacement to be larger for the S-shaped design case. As such, this simulation proves that adopting a S-shaped actuator design is better than a straight one in terms of deflection angle. However, there is a tradeoff i.e. the resonant frequency is lowered.



Fig. 2. Finite element modal analysis for the two different mirror designs using simulation software ABAQUS. The 1st design simulated is a mirror with S-shaped actuator design during (a) bending mode, with resonant frequency at 34.9Hz and a maximum Z-displacement of 1 μ m. (b) torsional mode, with resonant frequency of 72.1Hz and a maximum Z-displacement of 0.9 μ m. 2nd design simulated is a mirror with straight cantilever actuator design during (c) bending mode, with resonant frequency of 35.3Hz and a maximum Z-displacement of 1 μ m (d) torsional mode, with resonant frequency of 128Hz and a maximum Z-displacement of 0.36 μ m.

To evaluate the quality of the fabricated device, experimental displacement of the dcbiased device obtained under optical microscope is necessary so that comparison with expected theoretical displacement of actuator tip can be made. The theoretical displacement of the S-shaped piezoelectric actuator is derived from mathematical analysis. We assumed the Sshaped piezoelectric actuator to be made up of seven individual segments or actuators whose actuation performances are independent of one another. The following equations are used to evaluate the theoretical displacement of a segment of a piezoelectric actuator due to the contraction of the PZT film [22]:

$$\delta_n = \frac{3AB}{K} L_n^2 V d_{31} \tag{1}$$

$$A = S_{Si}S_{PZT}(S_{PZT}t_{Si} + S_{Si}t_{PZT})$$
⁽²⁾

$$B = \frac{t_{Si}(t_{Si} + t_{PZT})}{S_{PZT}t_{Si} + S_{Si}t_{PZT}}$$
(3)

$$K = (S_{Si})^{2} (t_{PZT})^{4} + 4S_{Si} S_{PZT} t_{Si} (t_{PZT})^{2} + 6S_{Si} S_{PZT} (t_{Si})^{2} (t_{PZT})^{2} + 4S_{Si} S_{PZT} t_{PZT} (t_{Si})^{2} + (S_{PZT})^{2} (t_{Si})^{4}$$
(4)

where δ_n is the theoretical displacement of the n^{th} segment of the S-shaped PZT actuator, L_n is the length of the n^{th} segment of the S-shaped PZT actuator, V is the applied voltage, S_{si} and S_{PZT} are the compliances of the structural Si layer $(6.0x10^{-12}\ Pa^{-1})$ and PZT thin film $(1.43x10^{-11}\ Pa^{-1})$ respectively [23], t_{Si} and t_{PZT} are the respective thicknesses of the structural silicon $(5\mu m)$ and PZT film $(2.5\mu m).$ Based on our previous study in ref [24], the transverse

piezoelectric coefficient d_{31} of the PZT film is assumed to be 130pmV^{-1} . The summation of all the seven individual segments that make up the S-shaped actuator is equivalent to the total theoretical displacement of the S-shaped PZT actuator:

$$\delta_{theoretical} = \sum_{n=1}^{7} \delta_n = \frac{3AB}{K} V d_{31} \sum_{n=1}^{7} \left(L_n \right)^2$$
(5)

3. Device microfabrication



Fig. 3. Microfabrication process flow for making the S-shaped PZT actuator and the mirror.

Figure 3 shows the microfabrication process flow of the 2-D MEMS mirror investigated in this paper. A silicon-on-insulator (SOI) wafer with Si device layer thickness of 5 μ m, buried oxide (BOX) layer thickness of 1 μ m and Si handle layer of 400 μ m was used as starting material. The process began with Pt/Ti/PZT/Ti/Pt/SiO₂ multilayer deposition on a SOI wafer as shown in Fig. 3(a). The SOI wafer was first oxidized at 1100°C to form a thermal oxide layer. After the oxidation, Pt (0.2 μ m)/Ti(0.05 μ m) thin films, to be used as bottom electrode materials, were deposited by DC magnetron sputtering. 2.5 μ m thick (100)-orientated Pb(Zr_{0.52}Ti_{0.48})O₃ film was formed by sol-gel deposition as reported in our previous study [25]. This (100) crystallographic orientation of PZT helps in maximizing the dielectric constant and electrical properties of the PZT film [25,26]. The top electrode Pt (0.2 μ m)/Ti(0.05 μ m) was then finally deposited by DC magnetron sputtering.

In Fig. 3(b), the obtained multilayers were etched by dry and wet methods. Through mask 1 and 3, the top and bottom electrodes were etched by using Ar ions respectively. Using mask 2, the PZT thin film was wet-etched using a mixture of HF, HNO₃ and HCl. In Fig. 3(c), a 0.8 μ m thick insulating oxide layer was deposited by RF-magnetron sputtering at room temperature. Contact hole openings were defined through mask 4 and etched by reactive ion etching (RIE) with CHF₃ gas. In Fig. 3(d), 1 μ m thick Pt metal lines, with Ti adhesion layer, were deposited by sputtering, patterned and etched using mask 5 and Ar ion. In Fig. 3(e), with mask 6, the thermal oxide layer, structural Si layer and buried oxide layer were etched by RIE using feed gases of CHF₃, SF₆ and CHF₃ respectively. Finally, in Fig. 3(f), the Si handle layer and buried oxide layer were etched from the backside using DRIE to release the actuator and mirror. The etchant gases used for Si and SiO₂ are SF₆ and CHF₃ respectively.



Fig. 4. Close-up photo showing the packaged MEMS mirror on a dual in-line package (DIP). The bond wires connect the bond pads on the device to the external pins of the DIP.

After the fabrication process, the device is assembled onto a dual in-line package (DIP) as shown in Fig. 4, with a spacer chip of $1200\mu m$ thick in between the device and DIP. The spacer chip helps to elevate the device from the base of the DIP, hence avoiding hindrance to the movement of the mirror plate during actuation. The bonds pads are connected by gold bond wires to the metal pins of the DIP.

4. Device characterization

4.1 Experimental setup

The schematic drawing of the experimental setup is illustrated in Fig. 5. The optical measurement setup consists of red laser source with an angle adjustable tripod, a DC voltage supply and a function generator for DC and AC characterization respectively. Incident light from the light source gets reflected by the mirror and propagates toward the screen with an ODA of 20, where θ denotes the mechanical deflection angle. The screen is placed and fixed perpendicularly to the reflected light when the device is initially unbiased. When the actuator is driven in ac mode, a mechanical deflection angle of $\pm \theta$ is introduced. The resulted reflected light will be deviated from the original light path with an angle of ± 20 and the light spot on the screen will be shifted by a distance $\pm L$. The value of θ can then be derived from the mirror. To enhance the piezoelectric characteristics, poling treatment was conducted on the PZT actuator at room temperature. A dc voltage of 20V, which is equivalent to a polarization electric field of 80kV/cm, was applied to the PZT actuator for 5 minutes, with the poling direction from the bottom electrode.



Fig. 5. Experimental setup for static and dynamic characterization of device where θ and 2θ denote the mechanical and optical deflection angles respectively.

4.2 DC response

When a dc bias is applied to the S-shaped PZT actuator, it bends and introduces a vertical displacement, causing the mirror to translate. As such, the laser spot will be displaced along the x-axis by a distance H on the white screen. Figure 6(a) shows the ODA (2 θ) obtained when various dc biases, up to 10V, were applied to the actuator. The top and bottom electrode

were biased as the driving and ground electrode respectively. At $1V_{dc}$ and $10V_{dc}$, an ODA of 0.22° and 3.35° were obtained respectively. To evaluate the quality of the fabricated device, comparison between the experimental (blue curve) and theoretical (red curve) displacement of the actuator tip is made and presented in Fig. 6(b). The experimental displacements of actuator tip at different dc biases were obtained by observing the biased device under the optical microscope. (1)-(5) were used to evaluate the theoretical displacement of the actuator due to the contraction of the PZT film at different dc bias. Figure 6(b) shows disparity between the theoretical mathematical approach and the results obtained from experimental method. This discrepancy may be due to lithographic inaccuracy and deviation in fabrication quality for the PZT film compared to our previous attempt in ref [24]. It may also be due to dynamic motion interaction between different segments of the S-shaped piezoelectric actuator, causing the overall actuation motion of the mirror plate to be damped.



Fig. 6. (a) Measured optical deflection angle versus DC driving voltage applied to PZT actuator. (b) Maximum displacement of actuator tip versus DC driving voltage applied to PZT actuator derived from experimental result and theoretical mathematical analysis.

4.3 AC response





Fig. 7. (a) A semi log plot illustrating the spectrum of optical deflection angle versus ac actuation frequency at $0.5V_{pp}$ for bending and torsional modes. (b) Measured optical deflection angle versus ac voltage peak-to-peak for bending and torsional modes. Bending and torsional mode occurs when the device is excited independently with ac signals of 27Hz and 70Hz respectively.

Figure 7(a) shows the semi-log plot of ODA with respect to ac voltage frequency varying from 1Hz to 1000Hz, while peak-to-peak ac voltage of $0.5V_{pp}$ was applied to the PZT actuator using a function generator. Two peaks are observed for bending mode at 27Hz and 230Hz, with ODA of $\pm 3.1^{\circ}$ and $\pm 0.96^{\circ}$ respectively. For torsional mode operation, a single peak is

observed at 70Hz, with an ODA of $\pm 0.84^{\circ}$. The resonant frequencies of 27Hz and 70Hz for bending and torsional mode respectively coincides with those simulation results obtained from finite element modal analysis i.e. 35Hz and 72Hz. The slight deviation in the measured and simulated resonant frequencies may be due to the consideration of the properties of silicon only during simulation, while neglecting the effects of other materials such as PZT and the electrodes.

In Fig. 7(b), the ac dynamic responses of the device under bending and torsional modes were investigated. In the biasing setup for bending mode operation, the actuator was excited with an electrical signal of frequency 27Hz and peak-to-peak ac voltages up to $3V_{pp}$ were applied to it. The device achieved an ODA of \pm 38.9° at $3V_{pp}$. The angle obtained at $3V_{pp}$ during dynamic actuation is significantly larger when compared to the ODA of 0.70° obtained at $3V_{dc}$ during static actuation. This phenomenon is due to the device attaining mechanical resonance behavior from the ac electrical excitation, resulting in maximum energy transfer from the ac electrical signal to the vibrating mechanical structures. For torsional mode operation, the biasing setup is similar to that in bending mode except that an ac signal with frequency of 70Hz is applied instead of 27Hz. An ODA of $\pm 2.1^{\circ}$ was observed at $3V_{pp}$ for torsional mode. For the same peak-to-peak voltage, the ODA for bending mode is much larger than that for torsional mode. This is because in bending mode, the mirror undergoes translational and rotational motion along the y-axis, whereas in torsional mode, the mirror only rotates along x-axis (Fig. 1a). As such, rotational motion of the mirror plate during torsional mode would not induce displacement of the reflection point as bending mode do, hence making bending mode more efficient in beam steering.

4.3.2 Mixed mode



Fig. 8. Schematic diagram illustrating the biasing configuration to produce 2-D scanning pattern. Two sinusoidal waveforms of different frequencies are inputted into a summing amplifier. V_B and V_T denote the peak-to-peak voltage for the ac signal frequencies 27Hz and 70Hz respectively. The output of the amplifier is connected to the device.



Fig. 9. Waveform obtained from different voltage output (a) Red dotted and blue solid curve show the respective output of the 2 functional generators when V_B and V_T are $0.5V_{pp}$. (b) Red dotted curve shows the resultant output of the summing amplifier V_{out} when V_B and V_T are $0.5V_{pp}$. Blue solid curve shows the fitting curve derived from (11).

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#147276 - \$15.00 USD (C) 2011 OSA In mixed mode operation, two ac electrical signals of 27Hz and 70Hz, corresponding to the resonant frequencies of bending and torsional modes respectively, were applied simultaneously to the devices so as to achieve 2-D scanning capability for the device. The biasing configuration to realize mixed mode operation is illustrated in Fig. 8. Two function generators, each carrying sinusoidal signals with frequencies of 27Hz and 70Hz respectively, were inputted into a summing amplifier MC1741C, Motorola. Unlike our previous approach in ref [27, 28]. where two ac signals of different frequencies can be applied separately to two different sets of actuators to achieve 2-D scanning effect, a summing amplifier is needed for our current device in this case as it has only a single PZT actuator and two bond pads available for biasing. With the summing amplifier, two ac signals carrying resonant frequencies corresponding to bending and torsional modes can now be combined into one superimposed signal, which will then be used to excite and drive the PZT actuator to achieve 2-D scanning effect. The values of the resistors R_1 , R_2 and R_f were chosen such that the summing amplifier has unity gain i.e. the output voltage (V_{out}) of the summing amplifier is equivalent to the summation of the input voltages (V_B and V_T).

To better understand and prove the effect of the summing amplifier on the two input ac signal, a HP/Agilent 54825A Infiniium Oscilloscope was used to detect the output signals. Figure 9(a) and 9(b) show the signals detected from the output of the function generators and summing amplifier respectively when both V_T and V_B were $0.5V_{pp}$. In Fig. 9(a), the red dotted curve shows the trace given by V_B i.e. the output of the first function generator with sinusoidal, 27Hz and $0.5V_{pp}$ waveform. The blue solid curve shows the trace given by V_T i.e. the output of the second function generator with sinusoidal, 70Hz and $0.5V_{pp}$ waveform. Both the red dotted and blue solid curves in Fig. 10(a) can be represented mathematically by (6) and (7) respectively:

$$V_{R} = -0.25 \sin[\omega_{R}(t+t_{1})]$$
(6)

$$V_T = -0.25 \sin[\omega_T (t + t_1)]$$
(7)

$$V_{out} = -[0.25\sin[\omega_B(t+t_1)] + 0.25\sin[\omega_T(t+t_1)]]$$
(8)

where $\omega_{\rm B} = 2\pi(27)$ Hz, $\omega_{\rm T} = 2\pi(70)$ Hz and t₁ is the amount of time shift needed to match the simulated sinusoidal curves with the oscilloscope traces

In Fig. 9(b), the red dotted curve shows the trace detected on the oscilloscope from the output of the summing amplifier i.e. Vout when two sinusoidal signals of 27Hz and 70Hz were inputted into the summing amplifier. The blue solid curve shows the fitting curve derived and plotted from (8). The close fitting of the blue solid curve with the red dotted curve in Fig. 9(b) confirms that the output of the summing amplifier is equivalent to the fitting curve (8) i.e. summation of the two sinusoidal signals created by the function generators and represented by (6) and (7). Such experimental confirmation is important as it allows us to ensure that the output superimposed signal from the summing amplifier remains controllable through the adjustment of the various parameters e.g. frequencies, V_T , V_B , of the 2 function generators. More importantly, it proves that the output signal from the summing amplifier retains the ac characteristics of the input signals from the function generators. This permits us to bias the device with resonant frequencies corresponding to bending and torsional modes simultaneously, allowing the device to achieve 2-D scanning effect with only one PZT actuator. The major peaks in Fig. 9(b) have also been numerically labeled and by matching these major peaks with the corresponding peaks in Fig. 9(a), we can interpret that these major peaks are largely attributed by the peaks of the blue solid curve (70Hz) in Fig. 9(a).



Fig. 10. The waveform obtained from V_{out} and captured by the oscilloscope (a) $V_B = 3V_{pp}$, $V_T = 0V_{pp}$ (b) $V_B = 0.8V_{pp}$, $V_T = 0.3V_{pp}$ (c) $V_B = 0.5V_{pp}$, $V_T = 0.5V_{pp}$ (d) $V_B = 0.3V_{pp}$, $V_T = 1V_{pp}$.

Figure 10 shows the different waveforms of V_{out} obtained from the oscilloscope for various combinations of V_B and V_T . Figure 10(a) illustrates a pure sinusoidal V_{out} of $3V_{pp}$ and frequency of 27Hz when $V_B = 3V_{pp}$, $V_T = 0V_{pp}$. As the value of V_B decreases and V_T increases from Fig. 10(a) to Fig. 10(d), more peaks are observed in the resultant waveform V_{out} . This is due to increased contribution from the 70Hz signal from function generator 2, as a 70Hz signal has more peaks per unit time when compared to the 27Hz signal from function generator 1.



Fig. 11. 2-D Lissajous scanning patterns obtained when various combinations of sinusoidal V_B and V_T were supplied by the two function generators and superimposed by the summing amplifier. (a) $V_B = 3V_{pp}$, $V_T = 0V_{pp}$ (b) $V_B = 0.8V_{pp}$, $V_T = 0.3V_{pp}$ (c) $V_B = 0.5V_{pp}$, $V_T = 0.5V_{pp}$ (d) $V_B = 0.3V_{pp}$, $V_T = 1V_{pp}$. The experimental conditions of the scanning line obtained in (a) were different from those obtained in (b)-(d) so as to accommodate the entire scanning line on the ruler scale.

Figure 11 shows the 2-D Lissajous scanning patterns obtained when various combinations of sinusoidal $V_{\rm B}$ and $V_{\rm T}$, according to the biasing conditions in Fig. 10, were supplied by the two function generators and superimposed by the summing amplifier. In Fig. 11(a), a straight horizontal laser trajectory line, corresponding to an ODA of \pm 38.9°, was obtained when a 27Hz, 3V_{pp} sinusoidal waveform was supplied by function generator 1 and function generator 2 switched off i.e. only bending mode occurs. In Fig. 11(b) to 11(d), mixed mode occurs as both function generators were switched on, causing 2-D Lissajous scanning patterns to be observed on the screen. As the magnitude of V_B decreased from $3V_{pp}$ in Fig. 11(a) to $0.3V_{pp}$ in Fig. 11(d), the horizontal trajectory length or ODA along the horizontal axis decreased from \pm 38.9° to \pm 1.85°. Similarly, for the vertical trajectory length, as the magnitude of V_T increased from $0V_{pp}$ in Fig. 11(a) to $1V_{pp}$ in Fig. 11(d), the vertical ODA increased from $\pm 0^{\circ}$ to \pm 1.18°. As such, the magnitudes of the horizontal and vertical ODA are governed by function generator 1 (27Hz) and 2 (70Hz) respectively. In addition, the values of horizontal and vertical ODA obtained during mixed mode operation correspond closely to the results obtained independently during bending and torsional modes in Fig. 10. For example, from Fig. 7(b), ODA of \pm 3.11° and \pm 0.79° were obtained at 0.5V_{pp} for bending and torsional modes respectively. These values are almost identical to those obtained during mixed mode in Fig. 11(c), where horizontal and vertical ODA of $\pm 3^{\circ}$ and $\pm 0.75^{\circ}$ were obtained. These matching results implies that the actuation voltages at two discrete frequencies do not affect the actuated displacement of the 2 scanning axes during mixed mode operation and the summing amplifier only acts as an interface to superimpose two ac signals from the function generators into one to excite the device. More importantly, the horizontal and vertical dimensions of the 2-D Lissajous pattern can be independently controlled by the two ac biasing signals which match with bending and torsional modes, hence allowing for flexibility and tunability.

To achieve better optical performance in terms of larger ODA and resonant frequencies, various optimizations can be made for our future works. For example, the sol-gel deposition of PZT thin film may be optimized further as reported data of PZT films with significantly larger piezoelectric strain constant, d_{31} , have been reported [29,30]. P. Muralt *et al.* have demonstrated 2µm thick sol-gel deposited (100)-PbZr_{0.52}Ti_{0.48}O₃ with piezoelectric strain coefficient, e_{31} , of 18C/m². This works out to be equivalent to a piezoelectric strain coefficient, d_{31} , of 257pmV⁻¹, which is significantly larger than the value of 130pmV⁻¹ estimated in this study. In addition, in order to increase the resonant frequency of the device without compromising on the optical performance and dynamic mirror deformation, the width of the PZT actuator may be increase the mass of it.

5. Conclusion

In this paper, development work on a novel dynamic excitation of an S-shaped PZT piezoelectric actuator superimposed with two ac voltages is explored and characterized through the evaluation of the 2-D scanning characteristics of an integrated silicon mircromirror. Instead of deploying a 1x10 PZT arrayed actuator design in our previous research attempt or multiple meandering PZT actuators for inner and outer frames, our current unique design of utilizing only a single S-shaped PZT actuator has successfully demonstrated 2-D scanning by having two superimposed ac voltages corresponding to bending and torsional modes.

Both DC and AC responses of the device were characterized. An ODA of 3.35° was achieved at 10Vdc. Bending and torsional modes occur when ac electrical signals with resonant frequencies of 27Hz and 70Hz are used to excite the device respectively. In mixed mode operation, two ac electrical signals of 27Hz and 70Hz were applied simultaneously to the devices using a summing amplifier, hence enabling the mirror to achieve 2-D scanning capability. The device has performed various Lissajous patterns successfully, exhibiting flexibility and tunability through the adjustment of biasing voltages V_B and V_T. Further reduction of the driving voltage is possible by reducing the thickness of the proof mass

beneath the mirror surface. However, the tradeoff is that there will be increase deformation of the mirror surface. Last but not least, we aim to include mirrors of smaller sizes in our future works as reduced mirror size will increase the resonant frequencies for the ac operation modes and improve the 2-D scanning performance of the device.

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