**19th International Conference on**
**Adaptive Structures and Technologies**
October 6-9, 2008
Ascona, Switzerland

# Development of a novel polymeric waveguide and micro actuator for micro scanning system

**Wei-Shu Hua[1], Wei-Chih Wang[2,3]*, Wen-Jong Wu[1]**
[1]Department of Engineering Science and Ocean Engineering, National Taiwan University, Taiwan
[2] Department of Mechanical Engineering, University of Washington, Seattle, WA, USA
[3]Department of Electrical Engineering, University of Washington, Seattle, WA, USA
Address: Room 113, University of Washington, Department of Mechanical Engineering,
Seattle, WA. 98106, USA
Tel: +1 206 543 2479, Fax: +1 206 685 8047
Email: abong@u.washington.edu, wshua@mems.iam.ntu.edu.tw, wjwu@ntu.edu.tw

## ABSTRACT

The main thrust of this paper is to eventually develop a fully integrated polymeric cantilever scanner for a far field endoscopic imaging application. The new technique deploys scanning instead of fiber bundle to capture optical image. In this paper, we present work on an integrated actuator system using an aerosol deposition of PZT thick film for the vertical actuator on a 1-D optical scanner system. Discussed here is the mechanical and optical design analysis for the resonating waveguide structure. In addition, a summary of the fabrication processes for the 1-D scanning device is provided. Lastly, experimental results of some preliminary mechanical and optical performance are shown.

**Keywords:** Scanning system, SU-8, polymeric waveguide, MEMS, aerosol deposition method.

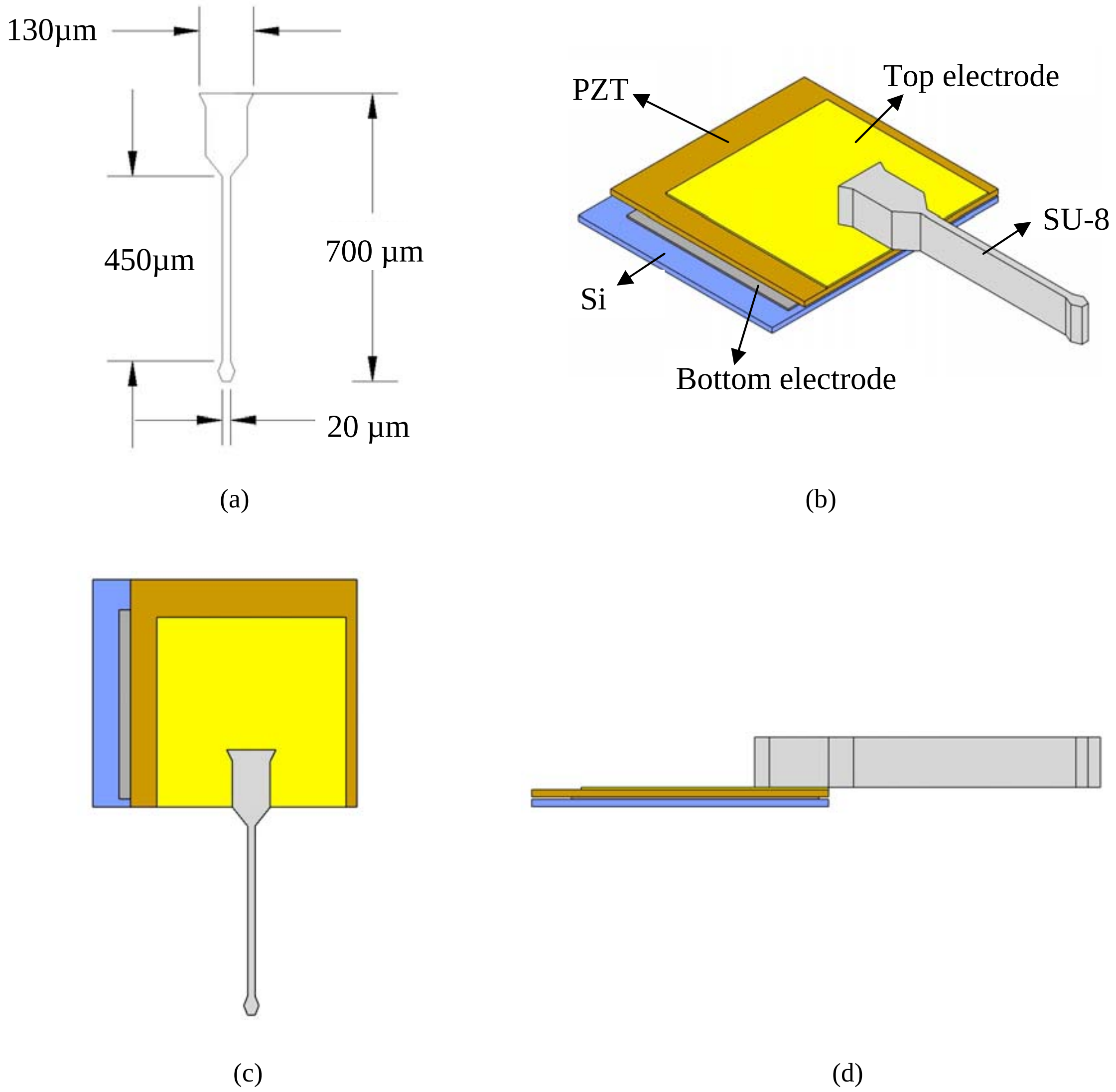
## 1. INTRODUCTION

In recently year, endoscopes are used extensively in medicine for diagnosis. The endoscopes can be classified into hard type and soft type endoscope. Hard type endoscope are consist of many optical lens, the volume are normally bulky. Besides, weak light source will cause worse visibility and it is inflexible will affect operates difficulty. On the other hand, soft type endoscope using optical fiber as image transmitter, it have flexible, easier operate and better visibility. For instance, Gastroscopy [1] and Olympus Gastrocamera [2] have been widely used to check for certain gastrointestinal conditions such as inflammation, ulcers and early signs of cancer. Therefore, dimensions limitation of scanner system and FOV (field-of-view) are the important issues and should be overcome.

To reduce the overall size while maintain resolution and FOV, a 2-D scanning scope was proposed [3, 4]. The basic design of the optical scanner includes a cantilever waveguide driven mechanical into resonant in x and y direction by a pair of mechanical transducers. In our previous work, we have shown a microfabricated SU-8 polymer cantilever waveguide that is electromechanically deflected by a 2-D piezoelectric actuator [3, 4]. In our current design, we propose to use the MEMS fabrication processes to fully integrate this scanner system where we hope in the near future to integrate the scanner with actuators, positions and light source as well as the detectors onto a single chip configuration. In this paper, we present work on an integrated actuator system using an aerosol deposition of PZT thick film for the vertical actuator on a 1-D optical scanner system

## 2. 1-D OPTICAL SCANNER SYSTEM

Our previous 2-D polymer cantilever waveguide scanning image acquisition [5], scanner is driven mechanical into 2-D raster scan by a pair of off-the-shelve PZT bimorph actuators. In this paper, we present a new actuator system using an aerosol deposition of PZT thick film on a 1-D optical scanning device (Figure 1). A FEM model of the cantilever with a length of 450 μm using elastic beam vibration equation and force equation for piezoelectric actuator is discussed. Preliminary finding on the actuator system as well as optical performance on this 1-D optical scanning system is presented.



(a) (b) (c) (d)

**Figure 1. Configuration the waveguide,** (a) Dimension (b) Overview (c) Top view (d) Side view

### 2-1. Waveguide Design

In our design, we utilize SU-8 2100 negatively tone photoresist (Microchem Corp.) as the waveguide structure. SU-8, especially, has wide practical applications popularity due to its superb imaging capabilities such as high-aspect-ratio (HAR), vertical side-wall profiles and dimensional control over the entire structural height. Besides, SU-8 is a suitable material as vibrating cantilever due to its excellent coating and processing properties as well as its chemical and mechanical stability. The main goal of this design is to obtain large deflect angle of the tip of the cantilever waveguide by using SU-8 as the material, vertically vibrated by actuating PZT film attached on the bottom of SU8 waveguide. To reduce the displacement without losing large deflection angle, a diamond shape tip design is also incorporated to create a pin-like boundary condition at the tip. This mass also acts as a lens aside from minimizing the tip displacement.

## 2-2. Fabrication Process

This process begins with a single sided polished p-type silicone wafer <100> orientation (fig. 2a). And spin coating a layer of photoresist and pattern it. Then evaporate 20nm Ti and 100nm Pt on the silicon surface to be the bottom electrode (fig. 2b). Owing to the high annealing and cure temperature, the PZT film will be deposited by aerosol deposition method and patterned on bottom electrode by using lift-off process. After PZT film is deposited, it is annealed at 650$^{o}$C for two days in the furnace (fig. 2c). Accordingly the top electrode is evaporated with 20nm Cr and 100nm Au on the PZT thick film (fig. 2d). Next step is to spin a layer of photoresist and the SU-8 photoresist is the latest layer to be coated on the top electrode layer (fig. 2e). The following is to pattern and develop the high aspect ratio imaging structure of SU-8 waveguide, then use ICP to etch through the silicon substrate to release the cantilever structure (fig. 2f`~2g).

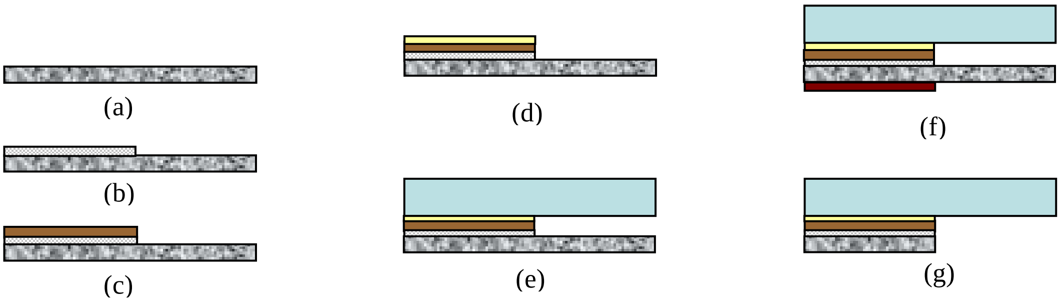


**Figure 2. Fabrication process** (a) Bare Si wafer (b) Plating bottom electrode (c) Deposited PZT thick film (d) Plating top electrode (e) Spin Coating SU-8 photoresist and pattern (f) Pattern photoresist on back side (g) Back side etch using ICP pattern photoresist.

## 3. ACTUATOR DESIGN

A PZT thick film was used as the mechanical actuation for the SU-8 waveguide. The idea of using PZT is due to its higher piezoelectricity coefficient and Young's modulus [6, 7]. Because of its manufacturing process is compatible with existing microfabrication process, it is also a material commonly used to provide mechanical actuation in MEMS device. In this actuator design, the SU-8 (an epoxy based polymer) waveguide is formed on top of the PZT thick film. The PZT depends on the external applied voltage, will produce strain on the film and thus create an expansion and contraction on the film. This piezoelectric effect is shown in equation 1 [6, 7].

$$S_p = s_{pq}^D T_q - g_{kp} D_k \tag{1}$$

Where $S_p$ is piezoelectric strain constant, $s_{pq}$ is elastic compliance matrix, the superscript D means under a constant electric displacement field, $g_{kp}$ is piezoelectric strain/ voltage constant, and $D$ is applied electric displacement field [8]. A FEM model based on the above equation was used for the piezoelectric actuator to generate the resulting displacement on the cantilever waveguide structure. COMSOL 3.4 finite element software was use for the analysis. Here the modal analysis (Figure 3) and the tip displacement and deflection angle of the waveguide as a function of applied voltages at first resonant frequency (Table 1) were performed. The material property of SU-8 photoresist is shown in Table 2. The PZT5A material property was used for the 5µm PZT thick film actuator (Table 3).

Deflection angle response of waveguide with 100V applied voltage near first resonant is shown in Figure 4. A large field of view can be obtained by having a large deflection angle without incurring a large tip displacement having a large added mass on the tip. In this case, we assume the system is derived with damping ratio obtained experimentally from the measurement. The results show that a displacement of d = 2 µm and a deflection angle of $\theta = 0.245°$ occurs @100V input applied voltage. A complete table of output displacement and deflection angle versus input voltage at 1st harmonic is shown in Table 1. Figure 5 shows deflection angle increases considerably from 0.049° (20V) to 0.736° (300V), the deflection angle stays linear with increasing applied voltages.

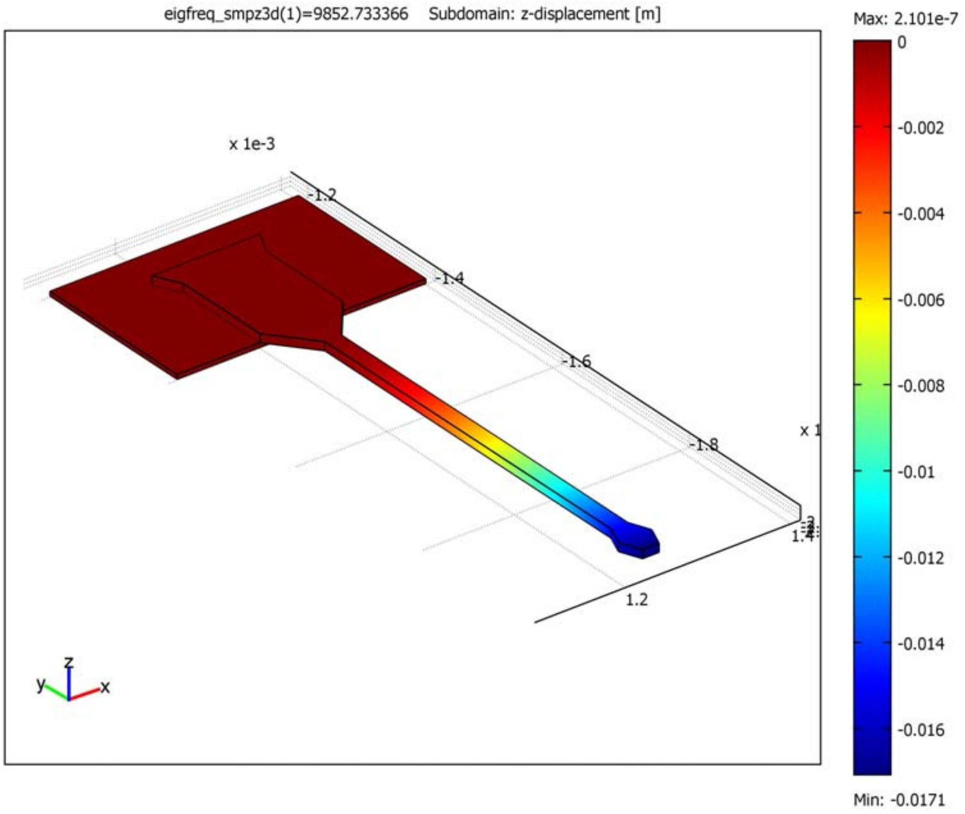


**Figure 3. Mode shape at first resonant frequency of the waveguide (with 5µm thickness of PZT)**

**Table 1. Tip displacement by applying voltage at 1st resonant frequency with 5µm PZT thick film**

| Applying Voltage | Displacement (m) | Deflection angle ( ° ) |
|---|---|---|
| 20V | $4\times10^{-7}$ , | 0.049 |
| 40V | $8\times10^{-7}$ , | 0.098 |
| 60V | $1.2\times10^{-6}$ , | 0.147 |
| 80V | $1.6\times10^{-6}$ , | 0.196 |
| 100V | $2\times10^{-6}$ , | 0.245 |

**Table 2. Material properties of SU-8 photoresist**

| Characteristics | Parameter | Conditions | Reference |
|---|---|---|---|
| Young's modulus, E | 4.02 (GPa) | In tension, post-baked at 95ºC, screw tensile testing machine | [9] |
| Poisson ratio | 0.22 | Post-baked at 95C, SM blend | [10] |
| Max stress | 34 (Mpa) | Hardbaked at 200C, lateral deflexion FEM analysis | [11] |
| Density | 1.237(g/ml) | 75% solids, viscosity is 45000 (cSt) | [12] |

**Table 3. Resonant frequency with 5µm PZT thick film**

| 5µm PZT thick film | Calculated resonant frequency (kHz) | |
|---|---|---|
| | 1st | 9.85 |
| | 2nd | 20.814 |
| | 3rd | 62.943 |

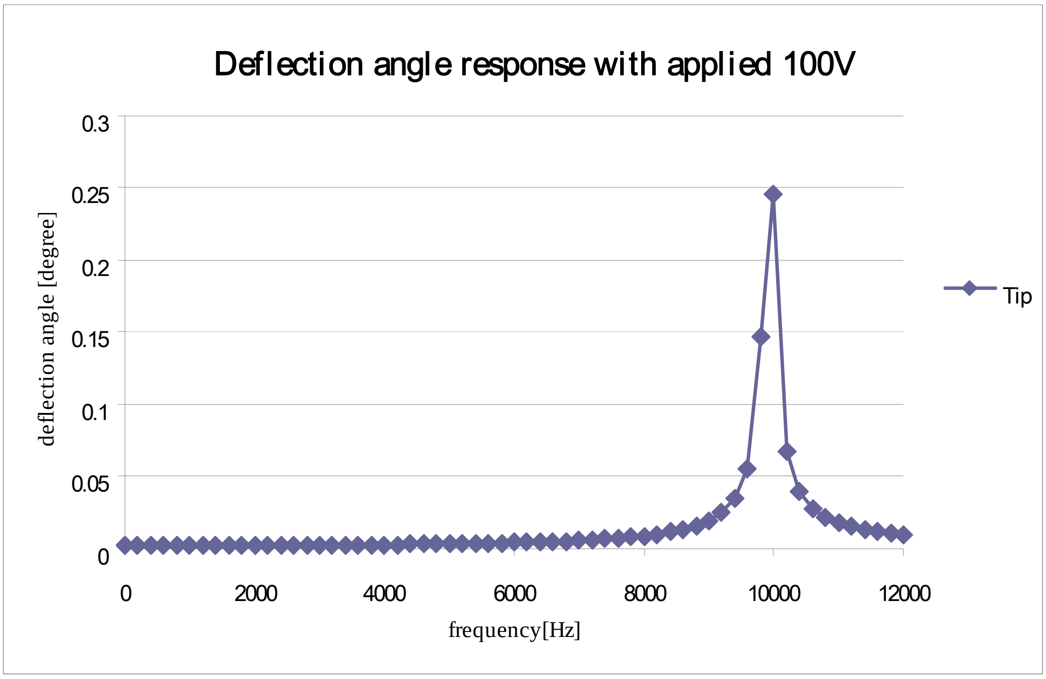


Figure 4. Deflection angle response with applied 100V

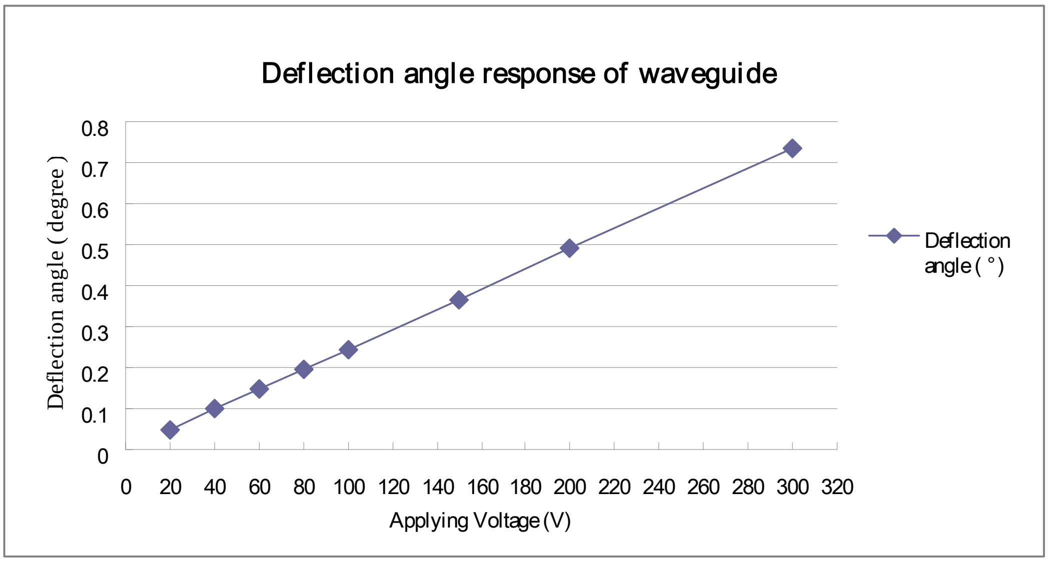


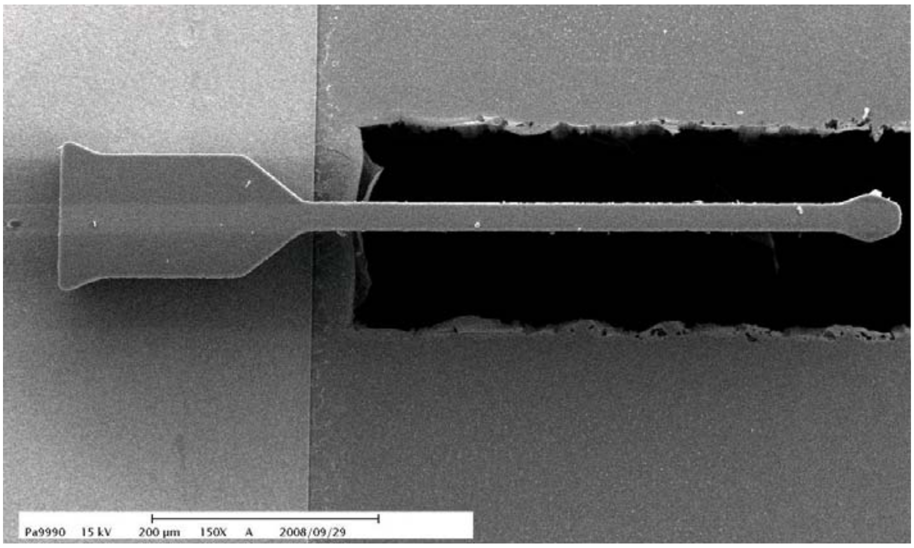
Figure 5. Group of applying voltage versus deflection angle with 5µm PZT thick film

## 4. RESULTS AND DISCUSSION

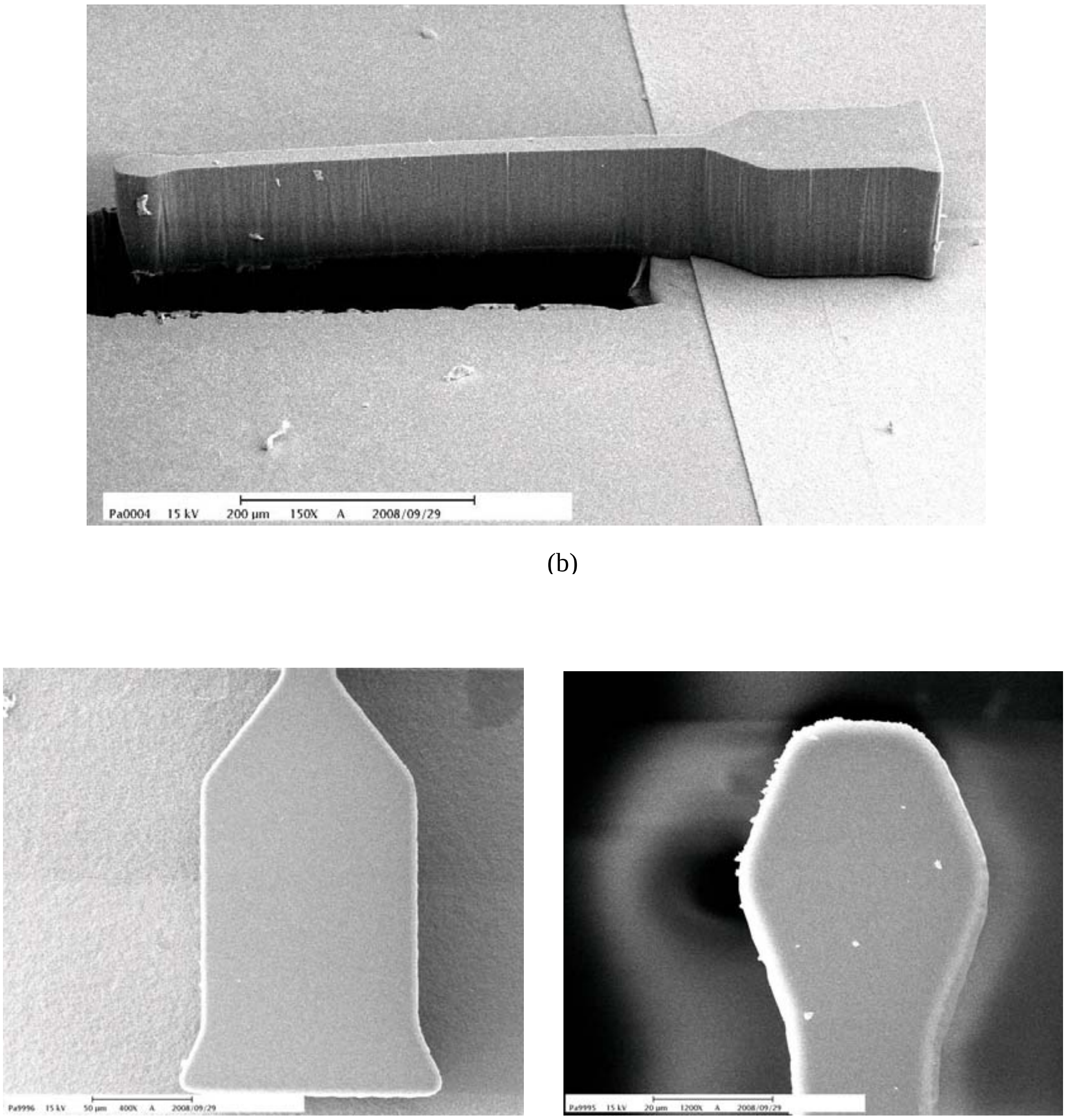
SEM micrographs of the SU-8 waveguide cantilever beam with tapered coupling section are shown in Figure 6. The light is introduced from the left, where the end face across section is 130 µm by 130 µm. The geometry is optimized to allow light from a regular 125µm cladding single mode optical fiber to coupled light easily into the waveguide without additional optics. The subsequent tapered waveguide helps guide the light into a 19 x 95 µm cantilever section of the waveguide, where the length of the cantilever is 450 µm long. The tip of waveguide has a diamond shape structure which has a dimension of 40 µm x 40 µm. The shape has dual purpose, one is to create an added mass at the end of the waveguide and the other is to help focus the beam. The thickness of SU-8 waveguide near its tip is 95µm. Here PZT thick film made by aerosol deposition method is 4.95µm. The overall thickness of the beam is about 5 times larger than what we eventually want the beam to reduce to. The current report is to show of process of how a SU-8 cantilever waveguide structure can be deposited on an aerosol jetted PZT thick film to form a scanning device.

Due to shortage of time, the device was not mechanically actuated. However, the deviation in the modal and displacement analysis between simulation and experiment result is likely to occur. This is expected since all polymer materials shrink after curing. From the previous fabrication, we expect SU8 film to shrink around 5% after all the process [14]. In this fabrication, we observed a reduction in the width of the cantilever beam of ~1.0 μm. The thickness is also reduced by about 5μm. Although specification table indicated that 100μm will be resulted based on recommended spin speed and developing process, the thickness is still reduced to 95μm in the end. This result agreed with our previous finding. The displacement of the cantilever will also be hard to compare between the simulation and experiment since the damping from the air, structure and material are unknown; therefore the actual displacement might be quite different. However, the input voltage versus the output displacement and deflection angle from the simulation and experiment should be linearly proportional. So a base line can be drawn from experiment for the simulation eventually. In the near future we plan to deposit a thicker film and also revise the beam design to incorporate the shrinkage in the SU8 to insure a good overall performance of the deflection.

One other likely causes for deviation between the simulation and experimental results is that a smaller than expected PZT actuation will be observed from the film actuator. This is likely due to manufacturing process of the PZT film. One of likely causes is that the powders although is ideally dispersed by a sweeping technique during the deposition, it is likely to collect in the same places; thus create lumps or surface roughness. The speed of deposit, the consume quantity of PZT powder and process time is also not quite as easy to control. Therefore the resulting film thickness is still not quite uniform. It is likely all these problems contributed to a lower than expected throughput from the film. However, these problems are currently been studied by our group. We will report our funding in the later publication.



(a)

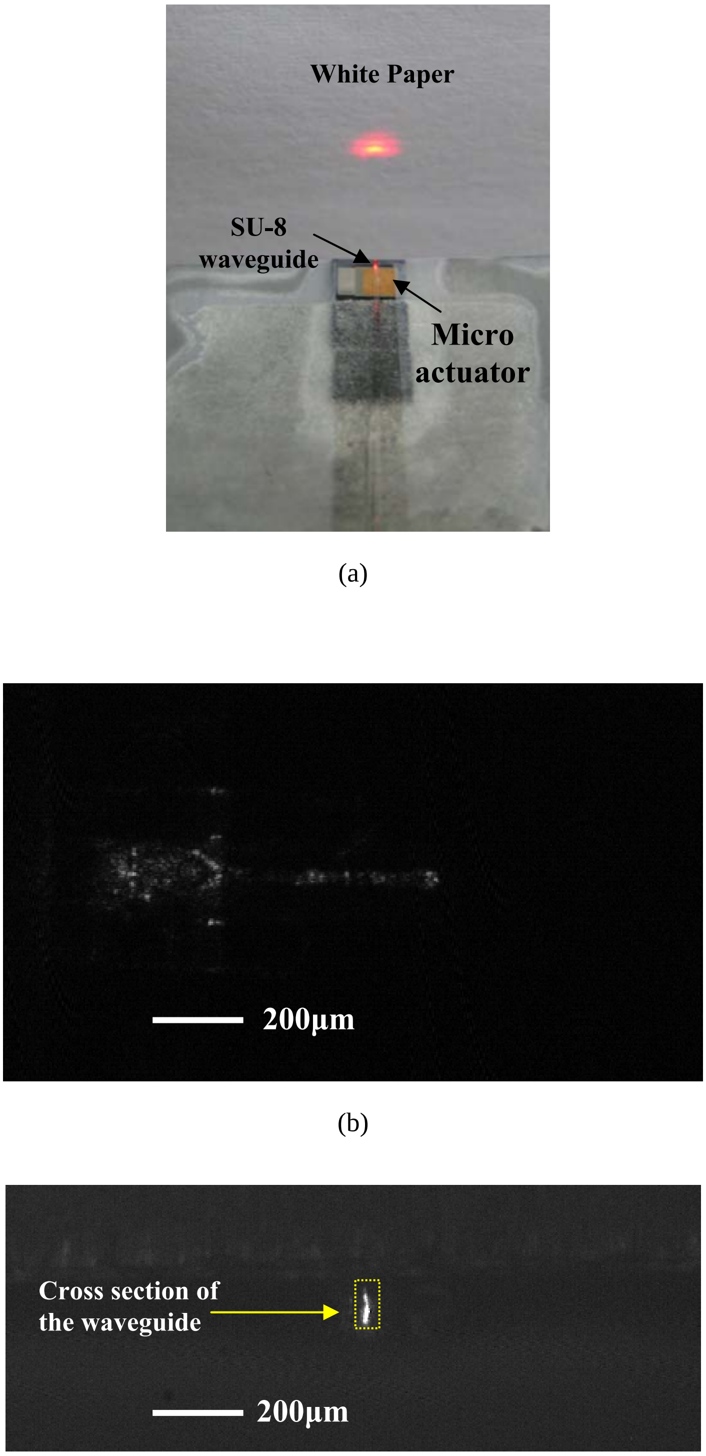


(b)

(c) (d)

**Figure 6. Configuration of SU-8 waveguide,** (a) Overview (b) Side view (c)~(d) Top view

The light throughput from the SU8 waveguide was tested using a 3mW 632.8nm He-Ne laser coupled to a single mode optical fiber (3µm core, 125 µm cladding, Corning). The fiber is end butted to the waveguide structure. Figure 7 shows light coming out from the end of the waveguide. The light is clearly visible from the end. Figure 7a shows light reflected off a white piece of paper placed about 1 cm away from the tip of the waveguide. Due to lack of proper light detection system, the light coupling efficiency was not measured. Although we know the absorption of the SU8 film is very low (< 0.3dB/cm) from our previous measurement [13], we did observe some light loss due to scattering from the rough surfaces. Figure 8 shows that light scattering is visible from the edges of the cantilever waveguide. This is due to the roughness on the sidewalls of the SU8. This can be contributed by the fact that the developing and baking process is still not quite optimized. Also sidewalls of the SU8 is not smooth due to ICP is over etching. Therefore SU-8 got etched slightly during the process. For more details on SU8 process with smooth sidewalls, please refer to our previous literatures [14]. We expected once fabrication parameters are controlled eventually the roughness of the sidewall can be reduced down to <10nm as shown in reference [14].



(a)

(b)

(c)

**Figure 7. Light output from waveguide cantilever end**

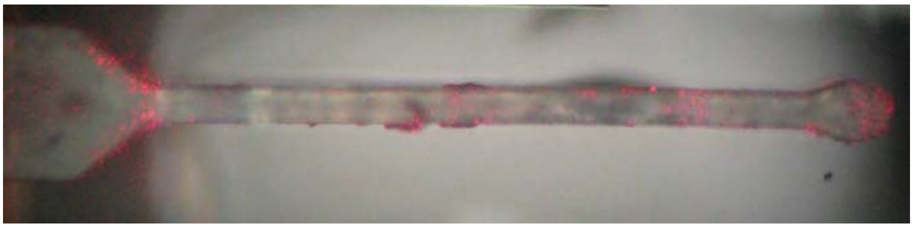


**Figure 8.Top view of optical waveguide cantilever, the length of the beam is 450 µm from the support to the tip.**

## 4. CONCLUSIONS

In this paper we present a 1-D optical scanning system using an actuator based on an aerosol deposition of PZT thick film. The work is still on-going to further improve the structure of SU-8 waveguide and enhance the property of PZT thick film. In the future, we will work toward the integration of components including 2-D PZT thick film actuators and light sources with a controller to create a system-on-chip for display system.

## REFERENCES

1. Complication of upper GI endoscopy. Gastrointestinal Endoscopy 2002; 55:784-793
2. Information on http://www.cameraquest.com/OlyGastro.htm.
3. Wei-Chih Wang, Fauver, M., Ho, J.N., Seibel, E.j. and Reinhall, P.G.(2002). Micromachined Optical Waveguide Cantilever as a Resonant Optical Scanner. Sensors and Acturator A (Physical), 102(1-2), 165-175.
4. Reynold Panergo, Chao-Shih Liu, Benjamin Estroff, and Wei-Chih Wang, “Polymeric waveguide design of a 2D scanner” SPIE, Volume 5768, Health Monitoring and Smart Nondestructive Evaluation of Structural and Biological Systems IV, Tribikram Kundu, Editor, May 2005, pp.450-460.
5. Christopher Takahashi, Hsiu-Jen Wang, Wei-Shu Hua, Per Reinhall and Wei-Chih Wang, “Polymeric Waveguide Design of a 2D display system,” Proceedings of SPIE Soc. Opt. Eng. 6177, 617719 ( March 2006).
6. H. W. Katz, “Solid State Magnetic and Dielectric Devices,” Wiley, New York, pp. 94-126, 1959.
7. Y. Wada and R. Hayakawa, “Piezoelectricity and Pyroelectricity of Polymers,” *Jpn, J. Appl. Phys.*, Vol. 15, No. 11, pp. 2041-2057, November 1976.
8. ANSI/IEEE Standard 176, *Piezoelectricity*, The Institute of Electrical and Electronics Engineers, Inc. September 1987.
9. H. Lorenz, M. Despont, M. Fahrni, N. LaBianca, P. Vettiger, and P. Renaud , "SU-8: a low-cost negative resist for MEMS", J. Micromech. Microeng **(**1997) **:** 121-124 : First journal paper of the EPFL team, from the work presented at the Micro Mechanics Europe'96 conference. Gives some deposition parameters and a simple mechanical characterization.
10. SOTEC MICROSYSTEM 11 avenue des Baumettes, 1020 RENENS, Switzerland, Tel: +41 21 693 67 51, +41 21 635 95 34, Fax: +41 21 635 94 41.
11. L. Guerin, M. Bossel, M. Demierre, S. Calmes, and P. Renaud, "Simple and low cost fabrication of embedded microchannels by using a new thick-film photoplastic", Proc. Transducers 1997**,** Chicago, (1997) : 1419-1422
12. Information on http://www.microchem.com.
13. Wei-Chih Wang, Reynold Panergo and Per Reinhall, "Development of a Microfabricated Scanning Endoscope using SU-8 Based Optical Waveguide machined Optical Waveguide", Proc. SPIE Vol. 5047, pp.305-313, Smart Nondestructive Evaluation and Health Monitoring of Structural and Biological Systems II, March 2003.
14. Reynold Panergo, Cheng-Sheng Huang, Choa-Shih Liu, Per Reinhall, Wei-Chih Wang, ” Resonant polymeric optical waveguide cantilever integrated for image acquisition,” Journal of Lightwave technology, Vol. 25, No. 3, pp. 850-860, March, 2007.