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RESEARCH ARTICLE

Lissajous Scan From an Optical Fiber Scanner

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ABSTRACT Optical devices are frequently being used in medical applications to image lesions and malignancies, and to assist with surgical procedures. The advances in micro-electro-mechanical systems (MEMSs) and optics led to the fabrication of flexible endoscopes as small as a few millimeters in diameter. The design of a sub-millimeter sized optical fiber scanner is presented in this paper. The proposed scanner consisted of a vibrating optical fiber that carried the laser light to the targeted imaging sample. The desired vibratory motion of the scanning device was obtained using a U-shaped electrothermal actuator where the asymmetry in the actuator's arm length caused the free end of the actuating device to bend allowing a bidirectional motion at its free end. The periodic square current wave passing through the actuator caused it to bend in a timely manner. By matching the signal frequency to the resonant frequency of the cantilever fiber and placing the cantilever appropriately relative to the actuator, the distal end of the fiber was allowed to follow a Lissajous scan. In optical scanners, the Lissajous scan pattern is normally obtained using a pair of actuators. This paper presents the design of a scanner providing a 2D Lissajous scan using a single actuator. Such a technique can provide basis for the development of sub-millimeter sized forward-viewing endoscopic catheters, whereas the smallest single fiber endoscope has a diameter of 1.2 mm. In the medical field, such a device has the potential to image small cavities of the body increasing the diagnostic yield of the medical procedures.

INDEX TERMS Electrothermal actuator, fiber optic scanner, MEMS, micro-cantilever, resonance vibration.

I. INTRODUCTION

Optical scanners are widely used in biomedical applications to image the inner sections of the body in real time and in a less invasive manner [1]. The advances in fiber optic systems led to the development of flexible endoscopes enabling high resolution images of narrow sections of the body thus reducing the number of biopsies required for a specific diagnosis such as cancer detection, microvascular oxygen tension measurement, chronic mesenteric ischemia, sub-cellular molecular interactions, etc. [2], [3], [4], [5]. Earlier developed standard white light endoscopes (WLEs) had limited ability to differentiate metaplasia from dysplasia. Such limitations were surpassed by enhancing the image contrast using dyes in chromoendoscopy or applying digital filters in narrow band imaging (NBI) [6], [7]. The increased use of endoscopic devices highly improved the diagnostic rate of cancers by permitting the visualization of early dysplasias which may lead to cancer development [7].

Other than biomedical applications, optical scanners find use in laser printers, barcode readers/scanners, micro displays, optical switches, 3D printers, laser scanning microscopes, etc. where the light beam is scanned in one or two directions [8].

The key component of an optical scanner is the actuator that allows the light beam to be scanned in one or two directions. Many optical scanners rely on the use of a moving mirror, where the mirror can be either oscillating or rotating allowing the light to scan in one or two axes. In the medical endoscopic field, the size of the device is the main factor that decides the area/organ that can be imaged using that device. The micro scanning mirrors find limited use in medical devices due to their limited field of view (FOV) [9]. To overcome such a limitation, a scanning fiber endoscope

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(SFE) was developed by Seibel et al., where the free end of an optical fiber was vibrated at resonance to scan the light over a large FOV without compromising its resolution [10], [11].

Many applications including biomedical imaging require the light to be scanned in two perpendicular directions to image a surface. A bidirectional scan is typically implemented with the use of two actuation devices which determine the scanning pattern from the vibrating tip of the fiber [1]. The different actuation mechanisms that find use in optical scanners are electrostatic, piezoelectric, electro-magnetic, electro-thermal, and shape memory alloys [12].

This paper reports the design of a novel fiber optic scanner where a bidirectional Lissajous scan from the vibrating tip of an optical scanner was obtained using a single actuator. The Lissajous scanning pattern is largely used in resonant fiber scanners and is normally obtained by exciting the optical fiber along two axes at different frequencies [13], [14], [15]. The work presented in this paper follows the work performed in [16] and [17] where an optical cantilevered fiber was vibrated in single direction using an electrothermal actuator providing excitation to the cantilever at a resonant frequency. The dimensions of the cantilever were obtained by considering the scanning frequency to be 2 kHz suitable for obtaining a good image resolution. In the original design of the prototype, the cantilever was vibrated in a linear scan, and the sample was proposed to be rotated at 10 Hz to achieve a near real-time frame rate of 20 frames per second (two frames per rotation). If the unidirectional scanning of $\pm 100\ \mu$m was implemented at an estimated scan rate of 1 kHz, 50 image diameters would be scanned per frame (1000*10/20), which corresponded to an angular resolution of 7.2° (360/50). If the scan frequency was doubled to 2 kHz, then the angular resolution would be improved to 3.6°.

The design of the actuator presented was simplified and optimized so that a bidirectional scan from the tip of the vibrating fiber was obtained using a single actuator. The work presented sets the basis for the development of a sub-millimeter sized catheter for real time imaging. In the medical field, such a device has the potential to image the small cavities of the body and increase the diagnostic yield of medical procedures.

The manuscript is organized as follows: Section II describes the computational analysis performed in COMSOL Multiphysics environment to simulate the behavior of the actuator in motion and the performance of the proposed device. The experimental work performed using the proposed scanner along with the sample fabrication and characterization is described in Section III. A discussion about the proposed scanner is reported in Section IV. The conclusions are presented in Section V.

II. COMPUTATIONAL MODEL

A bi-dimensional motion from a fiber tip was normally obtained by exciting the cantilever fiber in two directions. However, the use of a second actuator was not always feasible. Nevertheless, it was possible to generate an asymmetric/nonlinear excitation from a single actuator. A preliminary analysis was first performed through a simulation in ANSYS Workbench to show that the nonlinearity in the tip displacement of a cantilevered fiber tip (diameter $= 12\ \mu$m, length $= 2$ mm) can be obtained by a very small non-uniformity of the excitation at the base, as in Fig. 1.

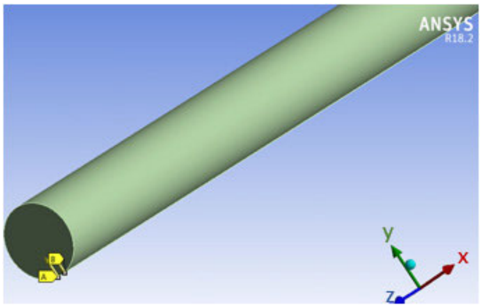


FIGURE 1. The non-uniformity of the base excitation.

A very small difference between the excitation at point A and B in Fig. 1, led the fiber tip to move in an elliptical manner (blue curve in Fig. 2). If a small out of plane excitation was included at point B in the design of Fig. 1, the fiber tip showed a corresponding higher out of plane motion. Thus, the fiber tip followed an elongated elliptical pattern at steady state as shown in the red curve of the phase plot of the tip displacement in Fig. 2.

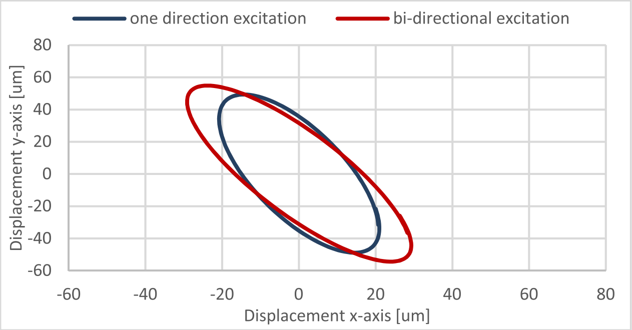


FIGURE 2. Phase plot of tip displacement using base excitation in Fig. 1.

In the MEMS field, u-shaped electrothermal actuators are the most used actuators that provide a bending moment at their free end. Thus, it is possible to obtain an in-plan bidirectional motion from a single actuator. In this category of actuators, the bending moment is the result of an asymmetric thermal expansion of the two arm beams which are either different in length [18] or in cross-section [19], [20]. The difference in length or geometry of the two arms in presence of an electric current cause different thermal expansion of two arms due to Joule heating. Consequently, one arm expands more than another and bends towards it [12].

A U-shaped electrothermal actuator having two arms with different cross sections was considered in this paper.

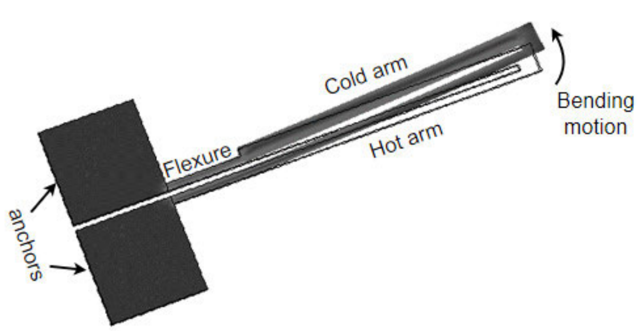


FIGURE 3. The schematic diagram of a U-shaped MEMS actuator having two arms with different cross section.

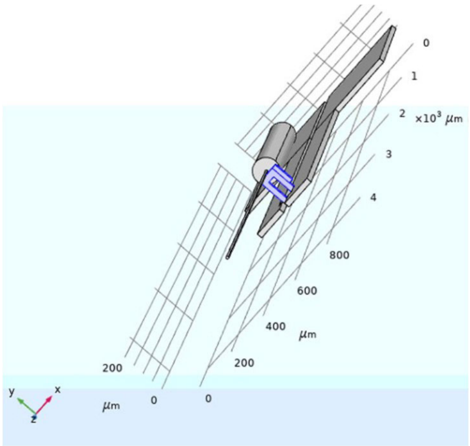


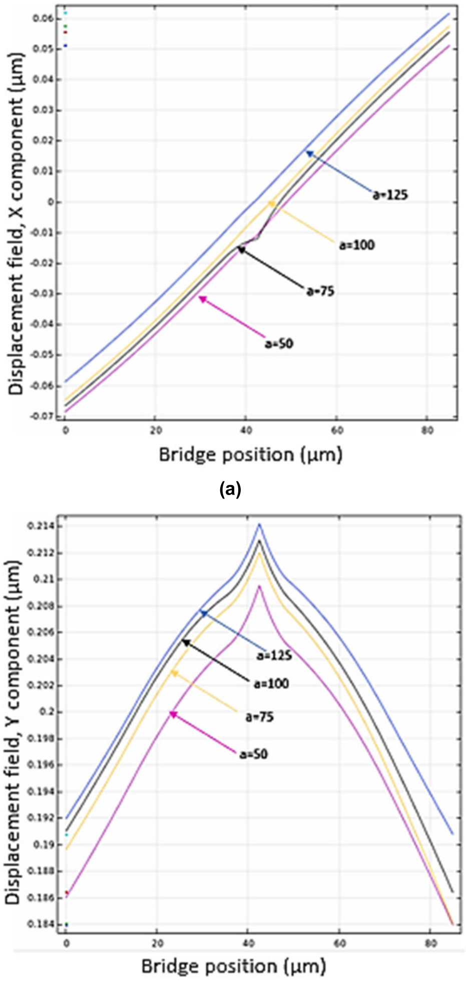
FIGURE 4. Schematic of an asymmetric bridge with cylindrical cantilever assembly.

A schematic diagram of such an actuator is shown in Fig. 3. There was a thinner flexure section connecting the wider cold arm to one of the anchors or connecting pads which facilitated the bending motion of the actuator tip.

The actuator-cantilever assembly considered in this paper was like that proposed previously in [16] and [21] with the difference of the shape of the principle actuating bridge. In the original work of [16], the key component of the actuator providing base excitation to the cantilever was a two-legged symmetric bridge where two arms of the same size expanded in the vertical direction in the presence of an electric current providing the excitation force in a single direction. Meanwhile, the design proposed in [21] presented a more complex actuator design which resulted from the combination of electrothermal actuators having different arm lengths and different cross sections. A bidirectional actuation force together with an asymmetric cantilever provided a circular scan pattern from the cantilever's vibrating tip.

In the current design, the anchors or connecting pads of the actuator in Fig. 3 were elongated, which helped to eliminate heat from the actuator and acted as a support for the cantilever. The actuator bridge in the current design was proposed to have shape like that of Fig. 3, having one arm 25 μm wide and the other 35 μm wide. The cantilever had a diameter of 12 μm. A detailed simulation of the vibration was performed in COMSOL Multiphysics. The schematic diagram of the proposed current design is shown in Fig. 4. In such a design, the actuator bridge provided a vertical motion and a horizontal motion towards the wider leg of the bridge. The intensity of the bridge displacement depended upon the position along the bridge as in Fig. 5.

Fig. 5a shows the bridge deformation along the vertical X direction for different values of parameter "a" which represented the flexure section of the actuator bridge, while Fig. 5b shows the displacement along horizontal Y direction. As can be seen from Fig. 5, the maximum vertical excitation corresponded to the center of bridge while the maximum horizontal displacement occurred at the edges of the bridge. Thus, to obtain a noticeable bridge displacement along both directions, it was better to place the cantilever in an off-centered position (1/4 or $\frac{3}{4}$ of the bridge arc length).



(a)

(b)

FIGURE 5. The displacement of bridge structure: a) along X direction; b) along Y direction.

In the case where the fiber was placed at 1/4 of the arc length of the bridge, as shown in Fig. 6, the system's

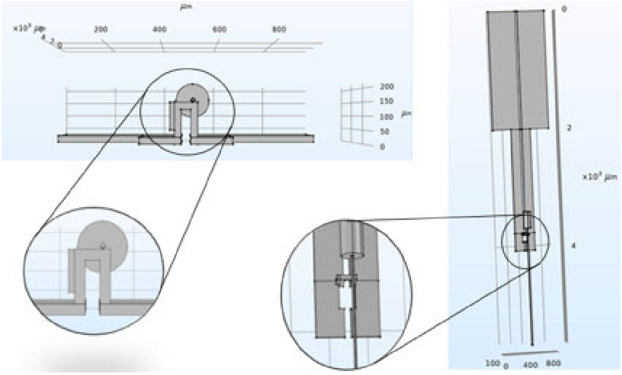


FIGURE 6. Schematic of an asymmetric bridge with cylindrical cantilever assembly.

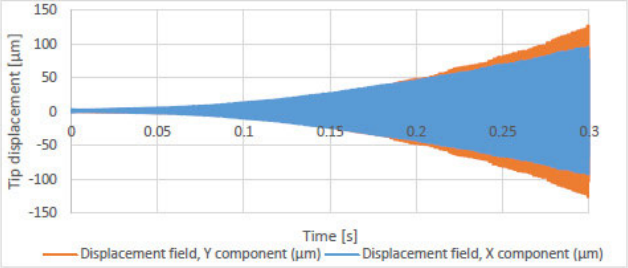


FIGURE 7. Time response of the cantilever beam tip actuated using an asymmetric bridge.

performance at resonance is shown in Fig. 7. In this Figure, the blue curve shows the fiber tip displacement along X direction, while the orange curve corresponds to the displacement along the Y direction. The continuous increase in the tip displacement was due to the non-damping effect considered in this analysis. When the damping effect was considered in the simulation, both displacements reached steady state, and the phase plot of Fig. 8 shows that the tip follows a Lissajous scanning pattern. It can also be seen that the scan needed to run for about 27 periods of the excitation signal to cover the full 2D area.

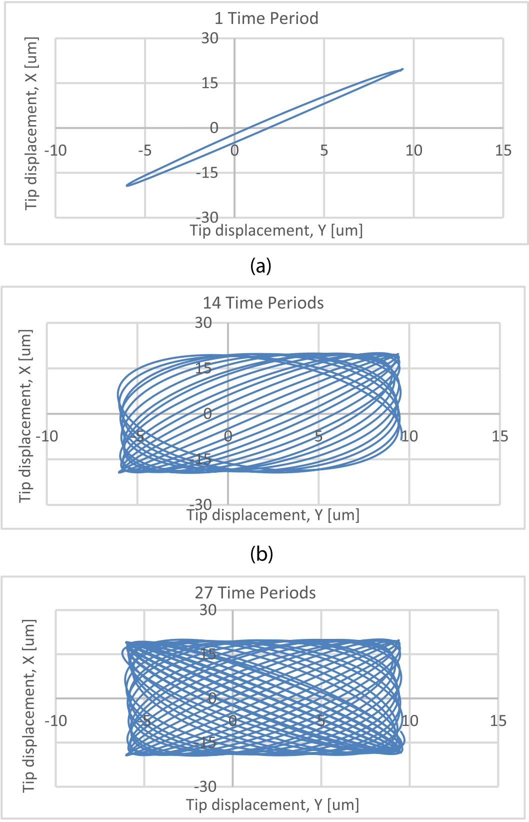
III. EXPERIMENTAL WORK

A. FABRICATION AND PACKAGING

The micro-cantilever was fabricated by either etching the tip of a double clad optical fiber having an initial diameter of 125 μm to 12 μm or using the heat splicing technique. Both cantilever fabrication techniques are explained in detail in [22].

The actuator bridge along with the connection anchor was fabricated by laser cutting a 25 μm thick brass foil in a pattern like that of Fig. 6. The actuating bridge was then manually lifted in the perpendicular direction.

The actuator and the cantilever fiber were fixed together with the help of SU-8 collars fabricated using soft lithography. The complete fabrication and packaging technique is discussed in detail in [16] and [21]. As from the computation model performed in the previous section, the cantilever was shifted towards the thinner arm of the bridge. The top and the side view of the complete sample inside the nitinol needle is shown in Fig. 9.

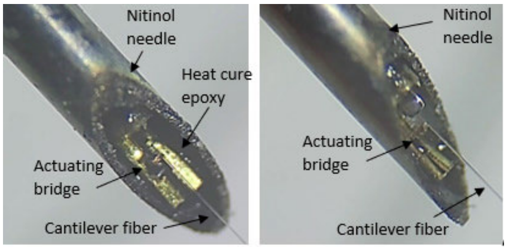


(a)

(b)

(c)

FIGURE 8. Fiber tip displacement at steady state excited by an asymmetric bridge in presence of damping: a) for 1 time period; b) for 14 time period cycles; c) for 27 time period cycles.



(a) (b)

FIGURE 9. The complete sample inside the nitinol needle: a) top view; b) side view.

B. CHARACTERIZATION

In a large number of optical scanners, the cantilevered optical fiber is vibrated at resonance to achieve a high tip displacement. The first resonant frequency of a cylindrical shaped cantilever beam is:

$$F = \frac{1.875^2}{4\pi}\sqrt{\frac{E}{\rho}\frac{R}{L^2}} \tag{1}$$

where E, ρ, R and L being Young's modulus, density, radius and length of the cantilever beam, respectively [23].

A square wave of current was passed through the actuator which expanded due to heat generation during the on-phase and returned to its original position during the off-phase. The continuous on-off cycle pushed the cantilever near its base causing it to vibrate. The frequency of the current signal was set equal to that of cantilever's resonant frequency so that it could vibrate at a maximum amplitude at a given excitation.

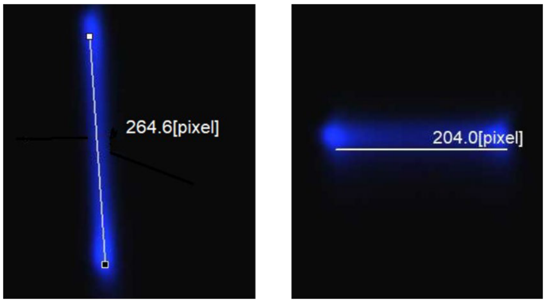
The proximal end of the optical fiber was connected to a blue laser light source (LP450-SF15, Thorlabs). The light was transmitted from the central core of the fixed portion of the fiber to the central core of the cantilever fiber. The distal end of the cantilevered fiber was slightly melted to create a lens effect such that the light exiting the fiber was focused on the target sample. The light from the vibrating tip was passed through the lens system and focused on a CMOS camera (STC-MBE132U3V, Sentec) to capture the front light image as stated in [21]. The CMOS camera was characterized by a frame rate of 60 fps and pixel size of 5.3 μm.

Since all the samples were fabricated and assembled by hand, there were some deviations in the angle of the actuating bridge that was lifted manually (± 5°), distance of the fixed end of the fiber relative to the actuating bridge (±10 μm), position of the fiber on top of the bridge (±5 μm), amount of epoxy applied to the sample, curing time, etc. Thus, the performance of each sample was different, as well as its resonant frequency (±1000 Hz). The resonant frequency of each sample was first monitored by manually changing the signal around its theoretical value and analyzing the tip displacement.

The sample was first vibrated at a small max current (0.95A) and a 50% duty cycle to detect the resonant frequency. It showed a linear vertical performance at 1.524 kHz (Fig. 10a), and a perfectly horizontal pattern at 3.942 kHz (Fig. 10b). Thus, the Lissajous pattern frequency must be within these two frequencies which was detected to be around 2.007 kHz. However, the scanning intensity was very small. To better evaluate the pattern, the system was run at a 20% duty cycle with a higher max current value. The Lissajous scan obtained at this point is shown in Fig. 11. The scanner was able to scan a quasi-rectangular pattern having sides composed of 192 × 104 pixels, and the scan had a fill factor of about 75%.

IV. DISCUSSION

The original proposed design in the previous papers [16], [17] to generate a linear scan from the fiber tip and rotating the whole assembly to get a 2D scan required a complex system. Thus, the actuator design was altered to get a Lissajous scan from its vibrating distal end using a single actuator.



(a) (b)

FIGURE 10. Front light captured from a sample at a frequency of: a) 1.524 kHz; b) 3.942 kHz.

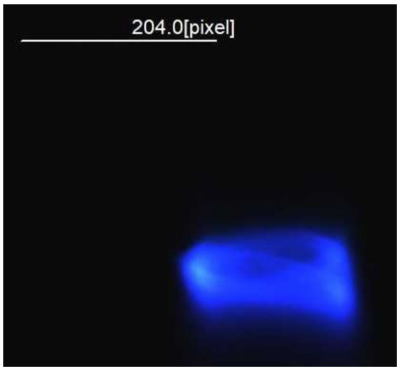


FIGURE 11. Lissajous scan from a sample at a frequency of 2.007 kHz.

The principal modification in the actuator design consisted of optimizing the asymmetry between the two legs of the bridge structure allowing its free end to move in both horizontal and vertical directions exciting the cantilever fiber in two directions. It is to be noted that the position of the asymmetry in the cantilever with respect to that of the actuator played a key role in the performance of the sample. Thus, the computation analysis performed in Section II provides the position of the cantilever on the actuating bridge where the performance was maximized.

As stated earlier, all the samples were handmade which imparted differences in the samples causing the resonant frequency and the performance of the samples to be different. Once the resonant frequency of a sample was determined, the performance of the sample was monitored by capturing the direct light from the vibrating tip through a CMOS camera. The variability among the samples caused by the position of the fiber on top of the bridge was decreased by adding a very small groove on the bridge surface where the fiber was slightly blocked. Similarly, the distance of the fixed end of the cantilever fiber from the actuating bridge was set by marking it on the fiber before assembling the sample or by assembly of the entire prototype under an optical microscope that allowed measurement of the distance during assembly. Similar measures were taken to reduce the variability in the angle of actuating bridge, and in the amount of epoxy used.

V. CONCLUSION

An optical scanner actuated by a U-shaped electro-thermal actuator is presented in this paper. The actuating portion of the actuator consisted of two asymmetric arms, which in presence of an electric current, expanded asymmetrically providing bidirectional actuation. From the computational analysis, by placing the cantilevered optical fiber at 4 of the arc length of the bridge, the cantilever showed a Lissajous pattern. Matching the frequency of the current supplied to the actuator to the resonant frequency of the cantilever, the distal tip of the fiber followed a Lissajous scan pattern.

The proposed design of the scanner was verified experimentally by fabricating some prototype samples. The resonant frequency of the cantilever was manually determined, and a square wave of current at that frequency was passed through the actuator. The front light image of the vibrating cantilever was monitored with the help of a lens system and a CMOS camera. A quasi-rectangular Lissajous scan was obtained with a fill factor of about 75%.

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Dr. Menon received several scholar awards, including both the Canadian Institutes of Health Research (CIHR) and the Michael Smith Foundation for Health Research Award.

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