AN ELECTROSTATIC MEMS SCANNER WITH IN-PLANE AND OUT-OF-PLANE TWO-DIMENSIONAL SCANNING CAPABILITY FOR CONFOCAL ENDOSCOPIC IN VIVO IMAGING

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ABSTRACT

We present an electrostatic MEMS scanner for a dual-axes confocal fluorescence endomicroscope to collect fluorescent images in three orthogonal planes of tissue with large field of view (FOV) at high frame rate. The scanner employs a novel lever-based dual-gimbal structure to perform coupling-free switchable XY/XZ/YZ two-dimensional (2D) beam scanning, and uses the parametric resonance excitation mechanism to produce large-amplitude motions. Test results show that the scanner can achieve large optical deflection angles, up to ±14.5° in the X-axis and up to ±10° in the Y-axes, and displacements up to 370μm in the Z-axis at atmospheric pressure, and its resonant frequencies of Z-, Y-, X- axes are near at 0.54kHz, 3.47kHz and 8.55kHz, respectively.

INTRODUCTION

Depth-resolved endomicroscopy shows great promise for biological and clinical applications in vivo. The ability of imaging the vertical plane provides histology-like images for diagnosis and quantitative studies in the natural direction of the disease development. The capability to perform axial scanning is required in addition to lateral scanning to obtain vertical cross-sectional images. For general purpose use, a miniature light-scanning engine that can provide large angular deflections and axial displacements is needed to image in either the horizontal or vertical plane.

Microscanners based on microelectromechanical systems (MEMS) technology can be fabricated with small size, high performance and low cost, and have been widely used in miniature biomedical optical imaging systems. Most these scanners produce in-plane 2D scanning to collect horizontal images only. An actuator must either move the objective lens or scan out-of-plane to collect vertical images. Recently several MEMS based axial scanning techniques, such as lens-moving actuators, tunable lenses, and deformable mirrors, have been used in some confocal and multiphoton imaging instruments [1,2]. However, integrating scanning mechanisms in two orthogonal directions into a compact scan-head for real-time in-vivo imaging is challenging. Our previous work [3] has reported a dual-axis confocal fluorescence endomicroscope with an outer diameter (OD) of 10mm for switchable horizontal/vertical cross-sectional imaging, in which a monolithically integrated MEMS scanner is placed in a post-objective position in the scan-head to reflect focused beams and perform either in-plane (XY) or out-of-plane(XZ) 2D scanning. Here, we demonstrate a new MEMS scanner with switchable XY/XZ/YZ 2D beam scanning capability for a more compact dual-axis confocal fluorescence endomicroscope to collect fluorescent images in three orthogonal planes.

DESIGN AND FABRICATION

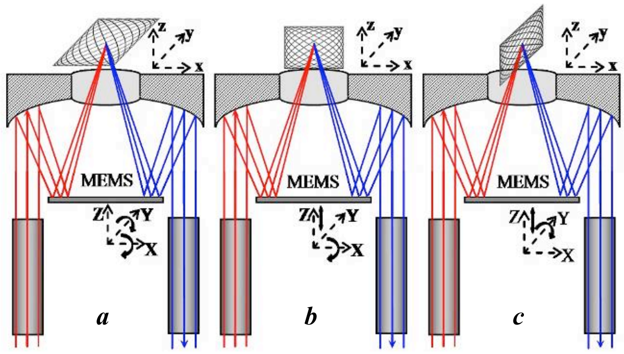


Figure 1: Schematics of an OD 5.5mm dual-axes confocal endoscopic probe using a single scanner to perform a) XY 2D scanning, b) XZ 2D scanning and c) YZ 2D scanning.

Dual-axis Confocal Endomicroscope

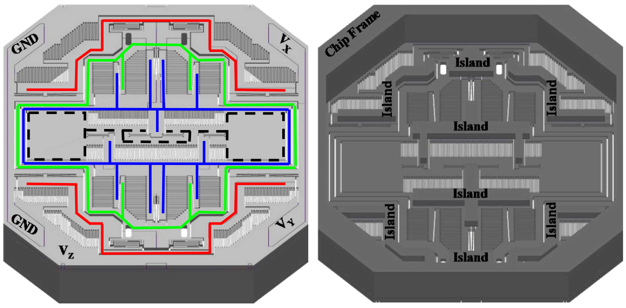
Figure 1 shows schematics of a dual-axes confocal endoscopic probe using a single scanner to perform switchable XY/XZ/YZ 2D scanning for imaging in three orthogonal planes. This instrument has an outer diameter of 5.5mm, and can be used for human GI tract in vivo imaging.

MEMS Scanner Design

To fit inside the probe tubing with a 5.0 mm inner diameter, the device chip is designed with an octagon shape with a dimension of 3.2mm (width) × 3.6mm (length) × 0.546mm (thickness), and its edges are cut for alignment and wiring, shown in Fig. 2a. A large cavity is opened on the backside of the chip to enable large amplitude of motions of the under the moving structures, shown in Fig. 2b.

The design of the scanner employs a dual-gimbal mirror structure suspended by two symmetrical lever-based suspensions for achieving independent motions in three orthogonal directions, naming the Z-axial translational motion, the Y-axial tosional motion and the X-axial tosional motion, shown in Fig. 3a, 3b and 3c, respectively. The suspension has a U-shape lever, which is coupled to the gimbal frame and the anchors through a multi-turn folded-beam spring and a pair of V-shape beam torsion springs, respectively. Through the lever-based suspensions, the dual-gimbal mirror structure can perform the out-of-plane translation along the Z-axis.

Three sets of comb drives are used to separately actuate the reflective mirror, the inner gimbal and the outer gimbal into rotation around the X-axis, rotation around the X-axis and translation along the Z-axis, respectively. These comb drives have an in-plane structure formed in the device silicon layer of a silicon-on-insulator (SOI) wafer with a thickness of ~45μm.



a) The front-side *b) The backside structures*

– *suspension* – *outer gimbal* – *inner gimbal* – *reflector*

Figure 2: Schematics of the designed scanner.

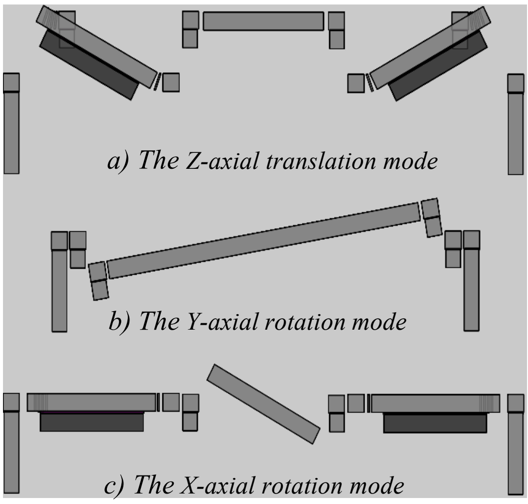
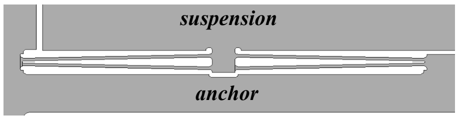


Figure 3: Schematics of three desired working modes.

The in-plane comb drives can enable resonant out-of-plane movements with large amplitudes by using parametrical excitation method. Based on this working principle, Lissajous scanning strategy is employed for imaging. To achieve high frame rate and generating dense and stable scanning patterns in either horizontal or oblique plane, frequencies of three desired working modes, namely the X-axial rotation mode, the Y-axial rotation mode and the Z-axial translation mode, are selected through structure optimization. Eigenfrequencies of the Z-axis, the Y-axis and the Z-axis are set at ~0.5kHz, ~3.5kHz and ~8.5kHz, respectively, which are mainly determined by the modification of the dimension of springs. Figure 4 shows the structural details of designed springs.

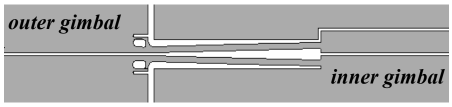
Device Fabrication

The scanner is fabricated in a 4inch SOI wafer with a 45μm device silicon layer, a 1μm silicon dioxide layer and a 500μm handle silicon layer. A cutting-free SOI micromachining process [3,4] is employed for fabricating the irregular scanner. Electrodes are electrically isolated narrow trenches opened in the device layer. The moveable structures with isolation trenches are supported by the

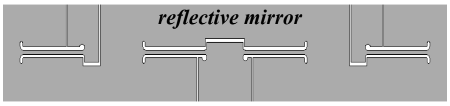


a) *centrally-clamped V-beam outer spring*

b) *serpentine spring*



c) *Y-axial V-beam spring*



d) *X-axial straight-beam springs*

Figure 4: Structures of the designed springs.

underneath islands formed in the backside silicon handle layer of the SOI wafer. And a backside cavity is formed for releasing moveable structures and enabling large movements. Link-arm structures, formed in the device silicon layer, are used to support the device chip during the whole-wafer processing. Figure 5 shows the schematic cross-section of the scanner with link-arms. After the whole-wafer processing, the device chip is detached from the wafer by breaking link-arms. Figure 6 shows photographs of the fabricated scanner.

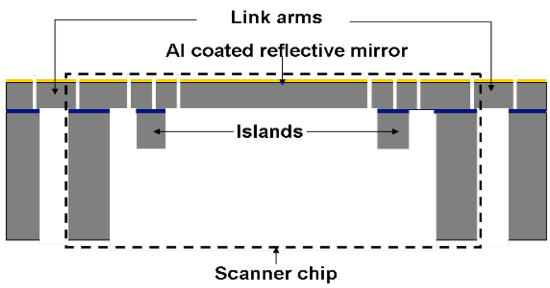


Figure 5: The schematic cross-section of the scanner with link-arms.

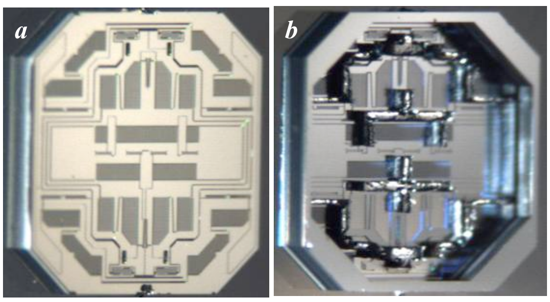


Figure 6: Photographs of the fabricated scanner. a) The front-side structure and b) the backside structure.

To provide highly reflective surfaces in both visible and near-infrared (NIR) (>80% reflectivity from 450-900nm), a ~70nm aluminum (Al) layer is evaporated onto the front side silicon. The mirror curvature and surface roughness were measured by an optical surface profiler (NewView 5000, Zygo). Measurement results show that the radius of the mirror curvature is ~1.8m and the root mean square (RMS) roughness is ~2nm.

PERFORMANCE CHARACTERIZATION

Due to the compact structure with a large aperture mirror, dynamic performances of the scanner, especially the out-of-plane translation motion, should be significantly effected by the air damping. Although a large and ~500μm deep cavity is formed under the movable structures, test results show that there was no observed resonant out-of-plane translational motion when the scanner was mounted on a flatten substrate and worked in the ambient pressure with high driving voltage. High vacuum packaging can efficiently reduce the damping for achieving large movements in MEMS applications. However, a separate vacuum-packaged optical MEMS device usually need an optical window to let light pass-through, that will increase the device size and makes it difficult to fit into a probe with a limited space. Additionally, high vacuum packaging of an endoscopic probe with the MEMS scanner, other mechanical and optical parts, is a big challenge. By analyzing the damping effects on the scanner mounted on the flatten substrate, the air in the cavity, that consists of the compact scanner, closed chip frames and flatten substrate surface, can be approximately treated as a fully-compressed gas when the scanner performing the out-of-plane translational movement near the balanced position, which is different with the situation when the scanner working in tilting modes. The damping force is mainly caused by the differential pressure, and its value is far greater than the electrostatic force. Increasing the open area in the device layer can reduce the differential pressure, but it conflicts with the requirements for large mirror size to match the optic design in this application. Here, we use a modified substrate with a deep non-closed cavity to mount the scanner chip for the air leaking. Thus, the air under the device layer can be treated as an incompressible gas, and the damping force can be dramatically reduced.

To characterize the performance of the scanner, we used a displacement sensor and a position sensing detector (PSD) to measure the out-of-plane displacement and the angular deflection, respectively. The scanner is mounted on the modified substrate and works at atmospheric pressure. For achieving large amplitude motions, the device was actuated into resonance by sweeping the driving frequency near at twice the eigenfrequency of the desired working mode.

Figure 7 shows frequency response curves of the out-of-plane translational displacement at different driving voltages and different duty cycles. A stable high gain region with >300μm vertical displacement was observed when forward sweeping the driving frequency, and a maximum amplitude of 370μm was obtained at ~1.09kHz with an 80V voltage and a 25% duty cycle. Figure 8 shows frequency response curves of the mirror in Y- and X-axes. Large optical scan angles up to ± 10° and ±14.5° were achieved in the Y-axis at 6.94kHz and in the X-axis at 17.08kHz, respectively.

Figure 9 shows motion images taken by a stereomicroscope when the scanner working in different 1D or 2D scanning modes. There are no other mechanical coupling motions observed when the scanner working in each of the independent 1D and 2D scanning modes.

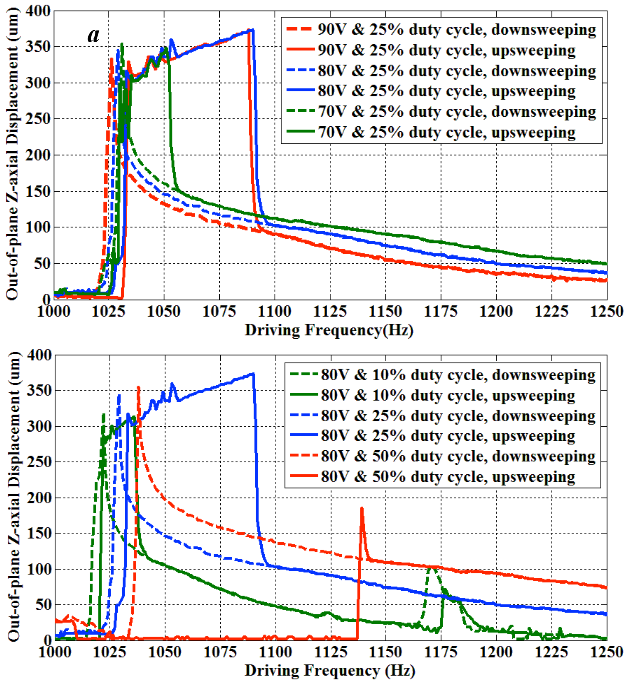


Figure 7: Frequency response curves of the out-of-plane Z-axial displacement at a) different voltages, and b) various duty cycles.

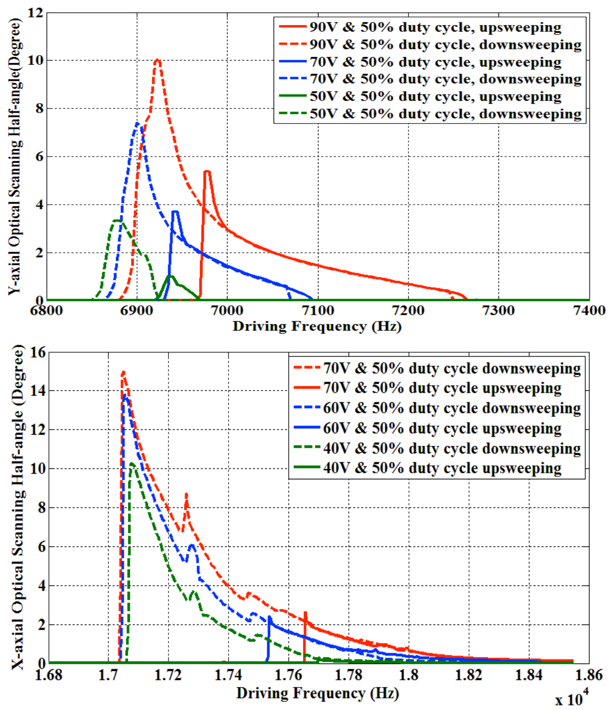


Figure 8: Frequency response curves of rotation amplitudes in a) the Y-axis and b) the X-axis at different voltages.

Based on these results, the developed scanner can meet the requirement for large FOV (≥ 600μm × 600μm in XY horizontal planes and ≥ 600μm× 300μm in XZ/YZ vertical planes) imaging with high frame rate (5~10 fps in three orthogonal planes).

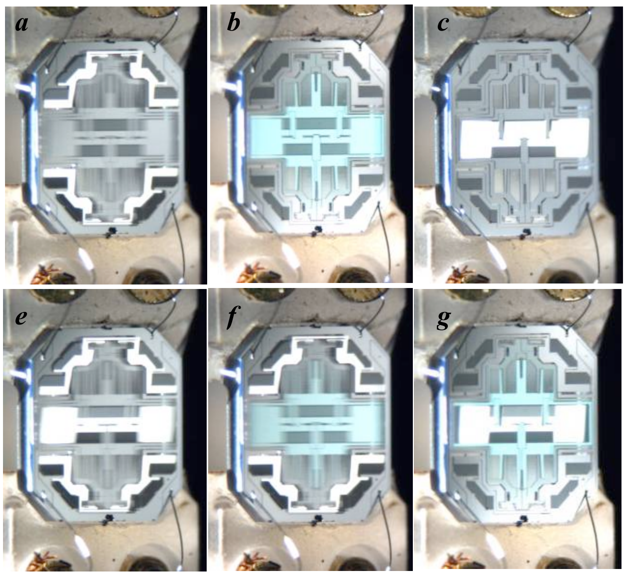


Figure 7: Motion images of the scanner when working in a) the Z-axis translation mode, b) the Y-axis rotation mode, c) the X-axis rotation mode, e) the XZ 2D scanning mode, f) the YZ 2D scanning mode and g) the XY 2D scanning mode.

CONCLUSION

A novel compact comb-driven MEMS scanner with a switchable XY/XZ/YZ 2D beam scanning capability is developed. Testing results show that this device can provide large optical scan angles and out-of-plane translational displacement under ambient pressure. The scanner can be integrated into an OD 5.5 mm dual axes confocal endomicroscope for collecting fluorescent invo images in three orthogonal planes of tissues with large FOV at high frame rate.

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