MEMS Electrostatic Double T-shaped Spring Mechanism for Circumferential Scanning

Xiaojing Mu, Guangya Zhou, Hongbin Yu, Julius Ming-Lin Tsai, Dennis Wee Keong Neo, A Senthil Kumar, Fook Siong Chau

Abstract—A novel microelectromechanical systems (MEMS) based micro-scanner is developed with the ultimate goal of integrating it into an endoscopic probe for use in clinical investigations. Micro-assembly technology is utilized to construct this device, which consists of an electrostatic based micro-actuator and a pyramidal polygon micro-reflector. A two-stage double T-shaped spring beam system is introduced to the actuator for displacement amplification, and as well for motion transfer from the translational movement of the in-plane comb drives to the rotation of the central ring-shaped holder. Meanwhile, an eight-slanted-facet-highly-reflective pyramidal polygon micro-reflector is developed using high precision diamond turning and soft lithography technologies. This reflector design requires only a small mechanical rotational angle to achieve full circumferential scanning. This MEMS device is developed with the goal of integrating it into an OCT probe that could provide an alternative for endoscopic optical coherence tomography (EOCT) applications that would have advantages of circumferential imaging capability, fast scanning speed, and low operational power consumption.

Index Terms — Microelectromechanical systems, optical coherence tomography, two-stage double T-shaped spring system, pyramidal polygon micro-reflector, soft lithography, full circumferential scanning

I. INTRODUCTION

Optical coherence tomography (OCT) is a promising technique for its cellular or even sub-cellular resolution (1-10 μm) [1] cross-sectional imaging of biological tissues, which is considered suitable for early detection and diagnosis of cancerous growth. For some clinic applications, for example, intravascular or gastrointestinal investigation, organs normally have tubular shapes. In order to reduce sampling errors, the whole cross-sectional images of the tubular organ need to be captured, thus full circumferential scanning (FCS) is highly desired. Early research efforts on FCS such as proximal catheter actuation [2] were capable of scanning at a speed of around 4 revolutions per second albeit with nonlinear motion due to physical inertia, friction and compliance of the device. Commercially- available micro-motors have also been employed to spin mirrors or prisms to achieve FCS [3-6].

In recent times, MEMS technology [6-22] has demonstrated strong potential in biomedical imaging applications due to its outstanding advantages of small size, fast scanning speed and convenience of batch fabrication. The recent development of a dual reflective MEMS micromirror based on bimorph actuators has further enriched and extended the MEMS technology for FCS in clinical applications [18, 19]. The MEMS integrated OCT probes normally utilize fibers and GRIN lenses to transmit and focus, and MEMS micro-mirrors to deflect the incident light beams, respectively. The image of a certain small tissue area can be detected and reconstructed three-dimensionally by mirror rotational scanning about the x and y axes respectively. Although it is convenient to realize the probe miniaturization by this configuration, the restricted scanning area makes it unsuitable for intravascular applications. In order to realize FCS scan, we have earlier proposed a compact four-pieces-in-one fiber-pigtail GRIN lens bundle EOCT probe [20]. This proposed configuration utilized multiple parallel incident light beams to drastically reduce the required mechanical rotation angle of the scanning mirror to achieve 360-degree circumferential scanning with only minimal increase in package size. The core light-scanning component placed at the distal side of the endoscopic probe is a pyramidal polygonal micro-reflector with four-highly reflective slanted facets actuated by MEMS chevron-beam electrothermal micro-actuators. This MEMS platform is orientated perpendicularly to the incident light beams. Although a large scanning range can be realized by chevron-beam micro-actuator, the high power consumption makes its surface temperature too high to be compatible with clinic medical bioimaging, a side-effect which had been reported previously [23-34].

Based on the configuration of the EOCT probe we developed before, we propose in this paper a MEMS micro-scanner that is actuated by electrostatic means instead. This MEMS device has the advantages of lower power consumption and higher scanning speed while maintaining the same scanning range of the previous design. One drawback of electrostatic actuation based MEMS devices is the relatively small scanning range due to its comb structure and working principle [35-45]. To avoid this limitation, a two-stage double T-shaped spring beam mechanism is introduced to convert
relatively small translational movements of the comb drives into a large rotational motion of the central suspended ring-shaped holder. The two-stage structure (as shown in Fig. 1(b)) provides displacement/angular amplification relative to a single-stage one. A pyramidal polygonal micro-reflector with eight highly-reflective slanted facets is developed to further lower the mechanical rotation angle required to realize full circumferential scanning. Once the micro-reflector is driven to rotate, a circumferential light scan will be realized. A circumferential tissue image may be reconstructed by recording the data from eight fiber optic “channels” sequentially or simultaneously. This newly-proposed configuration of an electrostatic MEMS micro-scanner based probe not only features the advantages of the previous one (compactness, small size and alleviation of the mirror curvature issue induced by residual stresses that might exist in traditional thin MEMS micro-mirrors), but also has a surface temperature that makes it suitable for clinic in vivo investigation and fast scanning capability.

This paper presents the theoretical modeling, structural design and FEM simulation of the MEMS mechanism in section II. Section III describes the detailed processes used to fabricate the microactuators and pyramidal polygon micro-reflector followed by the process of assembling these two parts together. Section IV demonstrates the characterization of this newly-developed device. Finally, the conclusions are provided in Section V. An optical scan angle up to near-360° and a rapid response time of 14 ms have been experimental measured.

II. DEVICE DESIGN

A. Structure Design of Rotational Mechanism

Figure 1(a) shows the schematic of the proposed MEMS-based micro-scanner. An electrostatic type MEMS-driven in-plane rotational platform is the actuation part, which has two lines of bidirectional-movable comb drives on the two sides (Fig. 1(b)). A ring-shaped holder is suspended in the center by a two-stage double T-shaped spring beams mechanism. In order to realize light scanning, an eight-slanted-facet pyramidal polygon micro-reflector is mounted on the ring-shaped holder. The translational movement of the two lines of comb drives in opposite directions results in the rotation of the central suspended ring-shaped holder and thus realizes the rotation of the pyramidal polygon micro-reflector. During operation, the micro-reflector can be driven to rotate clockwise and anti-clockwise by the electrostatic actuators. As schematically shown in Fig. 1(c), mechanical rotation angle of 22.5° both in clockwise and anti-clockwise direction could realize circumferential scanning (22.5°×2×8=360°) when eight external laser beams are shining on the eight slanted facets of the micro-reflector respectively at the same time.

Figure 2 shows the working principle of the two-stage double T-shaped spring-beam mechanism electrostatic based MEMS microactuator. It can be seen that the ring-shaped holder is connected to a pair of electrostatic comb-drive actuators (the movable fingers of which is suspended by the folded-beam supporting structure) using a double T-shaped two-stage beam mechanism. With this particular design, the translational movement provided by the micro-actuator can be eventually translated into rotation of the ring-shaped holder about an equivalent pivot point. At the same time, compared
with direct connection, the first stage T-shaped beam configuration (a and b), especially the vertically-arranged beam (a) as shown in Fig. 2, can help to release the deformation-induced stress at the anchor point of the horizontal beam (b) as well as in the beam itself, thus improving structure stability and reducing the undesired nonlinear effect. The introduction of the second stage T-shaped beam configuration (b and c) helps to translate and amplify the deformation of the first stage T-shaped spring to the spring c. When the driving voltage $V_1$ is energized, whilst keeping $V_2$ zero, the ring-shaped holder will be actuated to rotate counter-clockwise, and vice versa.

![Fig. 2. Working principle of the MEMS micro-actuator](image)

**B. Theoretical Study of the Two-stage Double T-shaped Spring Mechanism**

![Fig. 3. Simplified model for the two-stage double T-shaped beam spring mechanism of (a) the Whole system and (b) the Individual components](image)

Figure 3(a) shows the simplified model of the two-stage double T-shaped beam mechanism together with the ring-shaped holder, in which the holder is treated as a rigid body with only rotational degree of freedom. When an external force $F$ is applied onto this T-shaped beam mechanism, the free-body diagrams of each component can be schematically drawn, as in Fig. 3(b).

Under the effect of this external force, all the beams will be deformed (mainly bending deformation), therefore creating bending energy in the beam bodies, which can be described by

**Component 1:**

$$M_0 = F \cdot \left(A - \frac{D}{k}\right)$$

(1)

where

$$A = \frac{1}{3} l_2^2 + \frac{1}{8} l_1 \cdot l_2$$

$$D = \frac{1}{2} \frac{E \cdot I}{\frac{1}{4} I_2^2 + \frac{1}{16} I_1}$$

Considering the force and moment equilibrium of the structure, we get
$2M_1 + M_0 = F_1 \cdot 2l_2$

$M_1 = M_2 = M_6 = M_7 = M_1' = M_2' = M_6' = M_7'$

$F_1 = F_2 = F_3 = F_4 = F_5 = F_7 = F_1' = F_2' = F_6' = F_7' = F$

$F_3 = F_4 = F_3' = F_4'$

$M_0 = M_3 + F_3 \cdot l_3$

$M_3 = F_3 \cdot (l_4 + R)$

Substituting Eq. (2) into Eqs. (3), (4), (5), (6), (7), (8) and (9),

$$U_1 = \int \left( \frac{M_1 - F_1 \cdot x}{2EI} \right) dx + \int \frac{l_1 \left( (M_1 + M_0) - F_1 \cdot x \right)}{2EI} dx$$

$$= \frac{l_2}{2EI} \left[ \frac{2}{3} \cdot F_1^2 \cdot l_2^2 - F_1 \cdot M_0 \cdot l_2 + \frac{1}{2} \cdot M_0^2 \right]$$

Component 6:

$$U_6 = \int \left( \frac{M_6 - F_6 \cdot x}{2EI} \right) dx + \int \frac{l_1 \left( (M_6 + M_0) - F_6 \cdot x \right)}{2EI} dx$$

$$= \frac{l_2}{2EI} \left[ \frac{2}{3} \cdot F_6^2 \cdot l_2^2 - F_6 \cdot M_0 \cdot l_2 + \frac{1}{2} \cdot M_0^2 \right]$$

Component 2:

$$U_2 = \frac{(M_2)^2 \cdot l_1}{16EI}$$

Component 3:

$$U_3 = \frac{(M_3)^2 \cdot l_1}{16EI}$$

Component 5:

$$U_5 = \frac{(M_5)^2 \cdot l_1}{16EI}$$

Component 7:

$$U_7 = \frac{(M_4)^2 \cdot l_1}{16EI}$$

Component 4:

$$U_4 = \int \left( \frac{F_2 \cdot x - M_3}{2EI} \right) dx$$

$$= \frac{1}{EI} \cdot \frac{M_0^2 \cdot l_2}{(l_4 + l_3 + R)^2} \cdot \left( \frac{l_4^2}{3} + l_4 \cdot R + R^2 \right)$$

$$I = \frac{h \cdot w^3}{12}$$

where $E$ is the Young's modulus of structural material, $I$ is the moment of inertia of the beam structure, which is dependent on the beam width $w$ and thickness $h$, $R$ is the radius of the central ring-shape holder.

Substituting Eq. (1) into Eqs. (3), (4), (5), (6), (7), (8) and (9),

$$U_6 = F^2 \cdot \frac{l_2}{2EI} \cdot \frac{2}{3} \cdot l_2^2 - (A - \frac{D}{k}) \cdot l_2 + \frac{1}{2} \cdot (A - \frac{D}{k})^2$$

$$U_2 = U_3 = U_5 = U_7 = F^2 \cdot \frac{l_2}{64EI} \cdot (2 \cdot l_2 - (A - \frac{D}{k})^2)$$

$$U_4 = F^2 \cdot \frac{l_4}{EI} \cdot \frac{(A - \frac{D}{k})^2}{(l_4 + l_3 + R)^2} \cdot \left( \frac{l_4^2}{3} + l_4 \cdot R + R^2 \right)$$

As a result, the total bending energy in the two-stage double T-shaped spring beam mechanism caused by the external force can be calculated, ie

$$U_{total} = 2U_1 + 4U_2 + U_4$$

$$\delta = \frac{\partial U_{total}}{\partial F}$$

$$= \frac{2F}{EI} \cdot \left( \frac{l_2}{3} \cdot l_2^2 - (A - \frac{D}{k}) \cdot l_2 + \frac{1}{2} \cdot (A - \frac{D}{k})^2 \right)$$

$$+ \frac{l_4}{16} \cdot (2 \cdot l_2 - (A - \frac{D}{k})^2)$$

$$+ \frac{(A - \frac{D}{k})^2}{(l_4 + l_3 + R)^2} \cdot \left( \frac{l_4^2}{3} + l_4 \cdot R + R^2 \right)$$

It can be seen that the equivalent spring constant of this two-stage double T-shaped spring beam mechanism $k$ can be expressed by,

$$k = \frac{EI}{\frac{h \cdot w^3}{12} \cdot \frac{2}{3} \cdot l_2^2 - (A - \frac{D}{k}) \cdot l_2 + \frac{1}{2} \cdot (A - \frac{D}{k})^2}$$

$$+ \frac{l_4}{16} \cdot (2 \cdot l_2 - (A - \frac{D}{k})^2)$$

$$+ \frac{(A - \frac{D}{k})^2}{(l_4 + l_3 + R)^2} \cdot \left( \frac{l_4^2}{3} + l_4 \cdot R + R^2 \right)$$
\[ k \cdot \delta = F \]
\[ \Rightarrow \frac{1}{k} = \frac{\delta}{F} \]
\[ = \frac{2}{EI} \left( \frac{1}{3} \cdot l_2^2 - (A - \frac{D}{k}) \cdot l_2 + \frac{1}{2} \cdot (A - \frac{D}{k})^2 \right) \]
\[ + \frac{l_4^4}{16} \cdot \frac{(A - \frac{D}{k})^2}{(l_4 + l_3 + R)^2} \cdot \left( \frac{l_2^2}{3} + l_4 \cdot R + R^2 \right) \]

(16)

Equation (16) can be simplified as a function of \( k \), ie

\[ II_1 k^2 + II_3 k + II_2 = 0 \]

(17)

We then get

\[ k = -\frac{II_3}{II_1} \pm \frac{\sqrt{II_1^2 - 4 \cdot II_1 \cdot II_2}}{2 \cdot II_1} \]

(18)

where

\[ II_1 = I_1 \cdot I_2 \cdot A + I_3 \cdot A^2 \]
\[ II_2 = I_3 \cdot D^2 \]
\[ II_3 = I_2 \cdot D - 2 \cdot I_1 \cdot A \cdot D - 1 \]
\[ I_1 = \frac{l_1^4}{8EI} \cdot 4 \cdot l_2^2 + \frac{2l_2^2}{EI} \cdot \frac{l_2}{3} \]
\[ I_2 = \frac{l_2^4}{8EI} \cdot 4 \cdot l_2^2 + \frac{2l_2^2}{EI} \cdot l_2 \]
\[ I_3 = \frac{l_4^4}{8EI} \cdot 4 \cdot l_2^2 + \frac{2l_2^2}{EI} \cdot \frac{1}{\left( l_4 + l_3 + R \right)^2} \cdot \left( \frac{l_2^2}{3} + l_4 \cdot R + R^2 \right) \]

At the same time, the resultant rotational angle of the central ring-shape holder \( \theta \) can be calculated using beam deflection function [47],

\[ \theta = \frac{1}{EI} \cdot \frac{1}{\left( l_4 + l_3 + R \right)^2} \cdot \left[ \frac{l_2^2}{2} - (l_4 + R) \cdot l_4 + \frac{1}{3} \cdot \left( l_4 + R \right)^3 \right] \cdot M_0 \]

\[ = F \cdot \frac{1}{EI} \cdot \frac{1}{\left( l_4 + l_3 + R \right)^2} \cdot \left[ \frac{l_2^2}{2} - (l_4 + R) \cdot l_4 + \frac{1}{3} \cdot \left( l_4 + R \right)^3 \right] \]

\[ = F \cdot \frac{12}{E \cdot h \cdot w^3} \cdot \frac{1}{\left( l_4 + l_3 + R \right)^2} \cdot \left[ \frac{l_2^2}{2} - (l_4 + R) \cdot l_4 + \frac{1}{5} \cdot \left( l_4 + R \right)^3 \right] \]

(19)

After analyzing the two-stage double T-shaped beam mechanism, the model for the whole system involving the folded-beam suspension for the actuator is built as shown in Fig. 3(a), in which the folded-beam suspensions are represented by springs with equivalent spring constant of \( k_s \).

\[ k_s = 4 \cdot k_1 = \frac{4E \cdot hw^3}{l^3} \]

(20)

where \( l \) and \( w \) are the length and width of the folded-beam, respectively.

For further simplification, the whole system can be treated as a spring system as given in Fig. 3(a). It is obvious that when the electrostatic driven force \( F_a \) is applied at both sides, the resultant force \( F \) exerted on the T-shaped beam (namely \( k \)) can be deduced to be

\[ F = \frac{2F_a \cdot k}{k_s + 2k} \]

(21)

where \( F_a = N \cdot \varepsilon_0 \cdot \mu \cdot h \cdot V^2 \) (\( N \) is the number of finger pairs of the comb-drive micro-actuator, \( \varepsilon_0 = \text{8.85x10}^{-12} \text{F/m} \) is the vacuum permittivity, \( \varepsilon_1 = 1 \) is the relatively permittivity of air, \( V \) is the applied voltage, \( h \) and \( g \) are the finger thickness and gap, respectively.

Combining Eqs. (18), (19), (20) and (21), the resultant rotational angle of the central ring holder can be calculated.

In the current design, all the structures are fabricated using an SOI wafer with a 25 \( \mu \text{m} \)-thick device layer, ie all the structure thicknesses are equal to 25 \( \mu \text{m} \). Consequently, the structural dimensions of the folded-beam suspension are first determined to be 800 \( \mu \text{m} \)-long \( l \) and 6 \( \mu \text{m} \)-wide \( w \) to achieve moderate in-plane spring constant along the movement direction whilst providing sufficient support in the out-of-plane direction, according to our previous experience. At the same time, a comb-drive actuator with 372 pairs of fingers and 2 \( \mu \text{m} \) finger gap is adopted. From Eq. (19), it can be seen that a smaller beam width \( w \) of the T-shaped beam mechanism will result in a larger rotational angle. However, with the decrease of beam width, the structure strength in vertical direction will be reduced, thus affecting the operation stability of the ring-shaped holder. Moreover, a design with too small a beam width will also present a challenge to fabrication as well as the yield. As trade-off, the beam width of the T-shaped structure is selected to be 3 \( \mu \text{m} \). Calculations of the resultant rotational angle with different lengths of central bar \( l_3 \) and central spring \( l_4 \) show that most of the corresponding lengths of T-spring vertical beam \( l_1 \) and the horizontal beam \( l_2 \) to the peak value are located in the range of 150-250 \( \mu \text{m} \). In order to simplify the computation, \( l_1 \) and \( l_2 \) are selected to be 200 \( \mu \text{m} \).

Figure 4(a) shows a sample contour of the function of resultant rotational angle with the variables of central bar \( l_3 \) and central spring \( l_4 \) when T-spring vertical beam length \( l_1 \) and the horizontal beam length \( l_2 \) are selected as 200 \( \mu \text{m} \) and 200 \( \mu \text{m} \) respectively. The two-axis relationship curves of resultant rotation angle of the ring-shaped holder under different structure designs of the central bar spring mechanism under an applied 100 V DC are demonstrated in Fig. 4(b), from which 1000 \( \mu \text{m} \) and 800 \( \mu \text{m} \) are deduced to be the optimized values for the central bar \( l_3 \) and central spring \( l_4 \).
After reaching a maximum point (of around 20.5°), further increasing the length of the central bar ($l_3$) and central spring ($l_4$) will inversely reduce the resultant rotation angle at a relatively rapid rate. It is because of the limitation of the deformation compliance of the two-stage double T-shaped spring beam system in a relative small and unchanged designed chip area.

Using the designed structure parameters above, the equivalent model of the device is also built and analyzed using ABAQUS software. For simplification, an electrostatic driven force equivalent to 100 V actuation voltage is directly applied to the model during the analysis. Figure 5 shows the simulation results for the case of clockwise actuation, from which the in-plane rotation of the ring-shaped holder about the virtual center pivot caused by the translation movements of the side supports is clearly observed. The rotation angle is calculated to be 18.3° under the comb drive stroke of around 38 μm, which agrees well with the theoretical analysis result of 20.5° in Fig. 4.

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### III. Device Fabrication

#### A. MEMS Actuator Fabrication

![Fabrication process flow for the actuator](image)

**TABLE I**

<table>
<thead>
<tr>
<th>Item</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comb drive actuator</td>
<td>Finger pairs: 372</td>
</tr>
<tr>
<td></td>
<td>Finger gap: 2 μm</td>
</tr>
<tr>
<td></td>
<td>Finger width: 5 μm</td>
</tr>
<tr>
<td>Folder beam suspension</td>
<td>Length: 800 μm</td>
</tr>
<tr>
<td></td>
<td>Width: 6 μm</td>
</tr>
<tr>
<td>T-shaped beam suspension</td>
<td>Length of vertical beam ($l_1$): 200 μm</td>
</tr>
<tr>
<td></td>
<td>Length of horizontal beam ($l_2$): 200 μm</td>
</tr>
<tr>
<td></td>
<td>Beam width: 3 μm</td>
</tr>
<tr>
<td>Central Spring mechanism</td>
<td>Length of central bar ($l_3$): 1000 μm</td>
</tr>
<tr>
<td></td>
<td>Length of central spring ($l_4$): 800 μm</td>
</tr>
<tr>
<td></td>
<td>Beam width: 3 μm</td>
</tr>
<tr>
<td>Ring-shaped holder</td>
<td>Inner diameter: 140 μm</td>
</tr>
<tr>
<td></td>
<td>Outer diameter: 240 μm</td>
</tr>
</tbody>
</table>

### C. Simulation

![Simulation results for the proposed two-stage double T-shaped spring beam mechanism](image)
The proposed MEMS electrostatic microactuator is fabricated using a commercial foundry process called SOIMUMPs (MEMSCAP, USA). It begins with a blank double-sided polished SOI wafer; the top surface of the silicon layer is doped by depositing a phosphosilicate glass (PSG) layer and annealing at 1050°C for 1 hour in Argon (Fig. 6(a)). The thicknesses of device layer, buried oxide and substrate are 25 μm, 1 μm and 400 μm, respectively. After that, a metal stack of 20 nm of chrome and 500 nm of gold is patterned through a lift-off process to form electrical connection pads (Fig. 6(b)). Subsequently, using standard photolithography process, the desired structure patterns, including the actuator, the folded-beam and the T-shaped suspensions and the ring-shaped holder, are fabricated into a photo resist layer, acting as the hard mask. Then, all of these patterns are simultaneously transferred into the silicon device layer with one-step DRIE etching (Fig. 6(c)). Next, a frontside protection material is applied to the top surface of the silicon layer (Fig. 6(d)). The wafers are then reversed, and the substrate layer is lithographically patterned and this pattern is then etched into the bottom side oxide layer using Reactive Ion Etching (RIE). A DRIE silicon etches is subsequently used to etch these features completely through the substrate layer that is under the movable structure region as shown in Fig. 6(e). A wet oxide etch process is then used to remove the exposed buried oxide layer (Fig. 6(f)). Finally, the frontside protection material is stripped in a dry etch process to totally release the whole device (Fig. 6(g)).

Figure 7 shows the fully released MEMS micro-actuator. The inset on the top left corner is the zoom-in image of the ring-shaped holder, two-side flexure beam deformation of which will drive it rotate accordingly. The image of comb-drive actuator and the folded-beam suspension are shown in the bottom right corner inset.

### B. Micro-pyramidal Polygon Reflector Fabrication

The proposed general fabrication flow for the eight-slanted-facet pyramidal polygon micro-reflector, as summarized in Fig. 8, combines high-precision single-point diamond machining on a copper (Cu) substrate and the soft lithographic replication process with an elastomeric material known as PDMS. Firstly, the required mold is produced by diamond machining methods (inset in Fig. 8). The reverse of the mold will be replicated through a cycle of soft lithography and that serves as a PDMS mold for the next cycle of soft lithography. Particularly, liquid PDMS prepolymer (Sylgard 184 silicone elastomer - a base and curing agent of Dow Corning Corp - mixed in a 10:1 weight ratio) is poured onto the surface of the copper mold. After complete curing in an oven at 60°C for 2 hours, this thick PDMS substrate with the pyramidal polygon cavity pattern is peeled off. Meanwhile, the positioning pillar of the polygon is patterned on the SU8 (SU-8 2025, MicroChem Corp.) layer, which has been pre-spin onto the surface of a 4-inch polished silicon wafer. Then, the inverse of the pillar pattern (cylindrical pillar) with 80 μm is transferred from the SU-8 mold to a second PDMS mold. This PDMS mold is also carefully peeled from the mold substrate with the assistance of isopropyl alcohol (IPA) solution whereupon it is fully cured in the oven. Subsequently, a droplet of optical adhesive (Norland optical adhesive 83H, EDMUND) is applied on the surface of the cylindrical cavity that is pre-defined in the secondary PDMS mold. This cylindrical cavity defines the shape of the positioning pillar of the polygon reflector. There are also two other punched holes nearby to serve as alignment marks to precisely fix the relative positions of the polygon block and the pillar beneath. After that, the first layer of the PDMS mold of the polygon cavity is bonded together with the one of cylindrical cavities. Thus, the shape
of the whole micro-pyramidal polygon is defined by the optical adhesive that is trapped in the polygon-cylindrical cavity. The optical adhesive droplet fully cures in two minutes after it is exposed to ultraviolet light, thereby forming the pyramidal polygonal micro-reflector. Following this, the tough micro-pyramidal polygon replica is peeled off from the PDMS substrate. Finally, a 2000 Å-thick Au layer is deposited onto the pyramid polygon surface, by means of E-beam evaporation, to enhance its reflectivity.

The surface roughness measurement is performed by an optical profiler Veeco. The measurement results of the diamond turned master mold and the Au-coated polymer polygonal micro-reflector are shown in Figs. 9 (a) and (b), respectively. It indicates that the measured average surface roughness and root-mean-square roughness of the diamond turned master mold are 7.02 nm and 9.02 nm, respectively. Meanwhile, those roughnesses of the Au-coated polygonal micro-reflector are 48.95 nm and 61.90 nm, respectively. Such roughness difference between the diamond turned mold surface and the polygonal micro-reflector surface might be attributed to the thermal cycle and UV irradiation involved in the fabrication process. In OCT imaging applications, flat micro-reflector with surface roughness < λ/10 are normally desired, with the wavelengths of the near-infrared light source ranging from 930 nm to 1550 nm. As a result, our currently proposed micro-reflector shows promise to meet the requirements for the OCT imaging applications.

![Fig. 10. The set-up for assembly and schematic of device assembly](image)

![Fig. 11. The scanning electron microscope (SEM) image of the assembled MEMS electrostatic micro-scanner](image)

After the eight-slanted-facet pyramidal polygon micro-reflector and the electrostatic micro-actuator have been fabricated, they are assembled manually (as shown in Fig. 10). Initially, the microactuator chip is manually placed on top of the polygonal reflector and held with a vernier caliper with the actuator facing down. The position of the vernier caliper can be adjusted in both transverse and longitudinal in-plane directions as well as vertical out-of-plane direction by a three-axis precision positioning stage. Next, the circular ring-shaped holder of the actuation mechanism is aligned under a microscope to confirm that the mounting hole and the connection pillar are concentric before the actuator chip is lowered and the connection pillar inserted into the circular

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Fig. 9. (a) Measured surface roughness of a slanted facet of the copper master mold (average roughness Ra: 7.02 nm, root-mean-squared roughness Rq: 9.02 nm, the peak-to-valley difference Rt: 77.58 mm), (b) Measured surface roughness of the slanted facet of the Au-coated polymer polygonal micro-reflector (average roughness Ra: 48.95 nm, root-mean-squared roughness Rq: 61.90 nm, the peak-to-valley difference Rt: 950.67 nm)
ring-shaped holder. Finally, the pillar and the circular ring-shaped holder are bonded together by Araldite 2012 epoxy adhesive. Figure 11 shows a scanning electron microscope (SEM) image of the device after assembly.

IV. EXPERIMENT AND RESULTS

![Graph showing measured rotation angle vs. applied voltage and comb drive stroke vs. applied voltage curves.]

The comb drive strokes and rotation angles of the central ring-shaped holder under different driving voltages are characterized. During the test, a maximum voltage of 100 V DC is applied to ensure a high safety factor of stable and safe device operation. From the experimental results shown in Fig. 12, it can be observed that at a voltage of 100 V, the comb drive can achieve a maximum translational displacement of 38 μm whilst the central ring-shaped holder can be gradually driven to rotate nearly 20º in both clockwise and counter-clockwise directions.

![Image illustrating the setup of transient response experiment and measured transient response of the MEMS device.](https://example.com/image13)

Besides the static characterization of the MEMS microactuator, the transient response of the assembled MEMS device is also measured by connecting an AC Function/Arbitrary waveform generator (Agilent 33522A), a voltage Amplifier (A400D) and a digital oscilloscope (DL1520) to it. A position sensitive detector (PSD) (as shown in Fig. 13(a)) is utilized to detect the light trajectory scanned by the MEMS micro-reflector. A square wave with 22Hz frequency, 120Vp-p voltage, and 50% duty cycle is applied onto the sets of comb drive actuators that can drive the polygon micro-reflector to rotate clockwise.

The output of the detector together with the driving signal is directly captured by an oscilloscope in real time as shown in Fig. 13(b). The times taken for the detector to attain 90% values from 10% are measured to be around 82 ms and 96 ms. Compared with the electrothermal actuation based MEMS micro-scanner we developed and presented before, this relatively fast response (14 ms) undoubtedly makes the current device more competitive.

![Graph showing the applied voltage-optical scanning angle curve, laser scan trace lines and zoom in optical image of the MEMS micro-scanner.](https://example.com/image14)
Figure 14 is the optical scanning angle vs. applied voltage curve. To demonstrate the circumferential scanning capability, the MEMS device is driven into an oscillatory motion using an AC Function/Arbitrary waveform generator (Agilent 33522A) and a voltage Amplifier (A400D). A laser beam illuminates the micro-pyramidal reflector from above. The reflected beams from the slanted facets of the reflector project eight laser spots onto a cylindrical screen when the device is stationary. The device is then driven to oscillate by applying a sinusoidal input voltage with an amplitude of 80 Vpp and a frequency of 40 Hz. The captured scanning trace lines are shown in the inset of Fig. 14. Due to the limitation of the camera shooting angle, only half of the scan lines are visible in the figure. It is observed that under such a driving condition, a near-360° circumferential scanning range can be obtained. As the envisioned whole structure of the OCT system is shown in Fig.15, the developed double T-shape spring mechanism based MEMS micro-scanner could be the basis for FS-EOCT probes, which may help to make the probe miniaturized and compact.

![MEMS micro-scanner schematic](image)

**Fig. 15.** The schematic of the use envisioned for double T-shaped spring mechanism MEMS micro-scanner on OCT bioimaging

V. CONCLUSION

A novel MEMS micro-reflector based on electrostatic actuation that is aimed at achieving near-360° light beam scanning for OCT purposes has been successfully developed. It consists of a pair of electrostatically-driven comb-drives to actuate a two-stage double T-shaped spring beam mechanism and an eight-slanted-facet pyramidal polygonal micro-reflector with highly reflective surfaces. The polygon micro-reflector is developed using high precision diamond turning and soft lithography technologies. The two-stage double T-shaped beam spring mechanism translates the translational movement of the electrostatic actuator into in-plane rotation of the central suspended ring-shaped holder which holds the micro-reflector. This two-stage structure also provides displacement/angular amplification. During operation, a 38 µm comb drive stroke is achieved at 100 V, resulting in a rotation angle of around 20° in clockwise or counter-clockwise direction. Tests using light illuminated on the rotational polygon micro-reflector, verified that a near-360° circumferential scanning can be realized. At the same time, the response time of current device is measured to be 14 millisecond representing greatly improved performance over previous designs and good potential for the applicability of the device. In summary, this MEMS-driven micro-scanner could be the basis for FS-EOCT probes, which may help to make the probe miniaturized and compact. At the same time, the high surface temperature problem that existed in the previous design is probably alleviated by the current device.

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REFERENCES


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