360° Rotating Micro Mirror for Transmitting and Sensing Optical Coherence Tomography Signals

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Abstract

We have designed a micro actuator system for precise transmission and reception of bio-optical signals. Our system consists of a first-in-kind polysilicon micro mirror held stationary at a 45° angle on top of a 360°-rotating platform driven by a scratch drive array [1]. The entire system is designed with a 1-mm diameter size constraint. This constraint will allow the device to fit inside the tip of a catheter for use in biomedical endoscopy. We have developed two designs based on a commercial micromachining process to accomplish this. One mirror assembly is pulled into position at 45° while the other mirror assembly flips over itself into place. The benefit of the former mirror is that it can easily be coated with gold to improve reflectivity at the foundry. The benefit of the latter is that the optically-flat bottom surface of the polysilicon layer is used as the reflective surface of the mirror. Photoresist “hinges” [2] are used to allow this system to self-assemble by surface tension induced through heating.

Keywords
Micro mirror, MEMS, OCT

INTRODUCTION

Optical Coherence Tomography (OCT) has possibilities for use in “optical” biopsies. It is a compact technology that uses infrared light to image cross-sections of tissue on the micron scale. When used in a catheter system, OCT can collect images in vivo with resolution comparable to histology. This high level of resolution is only possible if the optics can be aligned appropriately with the tissue. Often times, the tissue depth of interest is perpendicular to the catheter, for instance, in tubular structures like blood vessels or the gastrointestinal tract, yet traditional medical endoscopes record images only from forward views. Newer implementations allow for imaging the sidewalls of tubular structures with the use of a 45° mirror. The usefulness of this approach is limited by the fact that these systems utilize a stationary mirror and thus do not allow for precise alignment with the tissue. Our actuator system is designed to overcome this limitation by allowing full control over the position of the mirror while attempting to image the walls of a tubular structure.

MOTIVATION

“Optical” biopsy could prove to be an invaluable diagnostic tool for many conditions. One such condition is Barrett’s esophagus. This pre-cancerous lining may affect upwards of one in sixty people [3]. Once diagnosed it is important to monitor closely. This condition may progress to esophageal adenocarcinoma, a cancer that is among the fastest growing ones in the western world [4]. Screening for dysplasia, the abnormal development or growth of cells, consists of taking four quadrant biopsies at two centimeter intervals along the entire length of the esophagus. This needs to be performed every six to twelve months. This method of monitoring is time consuming, inconvenient, costly, causes tissue damages in the patients, and with limited effectiveness because of the lack of comprehensive coverage on the entire length of the esophagus. By improving the resolution of optical biopsy, physicians will be able to monitor the entire region of interest in a minimally invasive manner without tissue damage. The goal of the work reported in this paper is to enable high-resolution OCT.

DESIGN

The ultimate goal of this work is to integrate the rotating 45° mirror inside the tip of a catheter for OCT endoscopic use, as illustrated in Figure 1.

![Figure 1. Conceptual drawing of the tip of an endoscopy system with the micro mirror on a rotating platform in place.](image-url)

The mirror is placed at a 45° angle opposite the optical fiber that channels the light beam from the operator to the catheter tip, bending the beam 90°. As the mirror platform rotates, a continuous full-circle scanning of tissues adjacent to the transparent sidewall is achieved. Also, the catheter can be continuously inserted while the mirror platform rotates, resulting in a spiral scanning path. A precise high resolution imaging of the entire inside wall of a tubular organ can then be collected from one fast, efficient, and precise endoscopic procedure.
There are several key design considerations in order to achieve these goals. First, and most importantly, the device must fit inside a 1 to 2 mm-diameter cylinder. Currently, micro motors that satisfy this volume constraint are not commercially available. Second, precisely assembling pre-fabricated and polished mirrors of that size onto a rotating platform is impractical. Microelectromechanical systems (MEMS) technology offers the ability to create sub-mm-sized motors and process integration by leveraging the sophisticated photolithographic tool sets from the IC industry. The research described in this paper demonstrates several novel uses of MEMS technology to achieve an integrated mirror-rotation platform.

There are three main aspects to the design of this device: actuated rotating platform, mirror design, and assembly, as described in the following subsections.

**Actuated Rotating Platform**

There are several essential design requirements for the motor that both supports and actuates the rotating platform, which include compactness, stability, sufficient force generation, low heat generation, moderate drive voltage, and low power consumption. The earliest MEMS-fabricated planar motors utilized electrostatic drive from stators around the perimeters of the rotors [5 – 7]. However, there was no convenient way to use this type of motors to support the mirror and the load carrying capability was modest. Also, the required voltage to actuate them often exceeded 50V. Finally, the stepping angle was inversely proportional to the number of stators in the design. To achieve a fine motion resolution of several hundred steps per rotation, a minimum of several hundred stators and a corresponding number of electrical interconnects were needed, which is impractical.

More recently, compact electrostatic actuation mechanisms were developed as an alternative to the early micro motors. An array of “scratch drives” was demonstrated with the capability of turning a rotating platform with precisely controlled steps at a substantially reduced drive voltages [8]. Based on electrostatic force leveraged from a parallel plate arrangement, the rotary scratch drive array has been shown to develop load carrying capability sufficient to rotate large fan blades in either air or liquid media [1]. The array of scratch drives is located inside the rotating platform with only a few microns in height, resulting in a highly space-efficient design. The most important advantage is that scratch drives allow precise control of the rotating speed, directions, and turning steps, which is ideal of OCT applications.

In this work, two different size versions of rotating platforms based on scratch drive arrays have been implemented for large and small mirrors. The small rotary scratch drive array is 530 µm in diameter with nine scratch drives, and the larger version is 880 µm in diameter actuated with 12 scratch drives. Figure 2 is the layouts of these two versions. The design and size of each individual scratch drives have been optimized to develop precision motional control and sufficient load carrying capability [8].

![Figure 2. Layouts of two rotary scratch drive platforms with (a) 530 µm diameter and nine scratch drives, and (b) 880 µm and 12 scratch drives.](image)

**Mirror Designs**

With the rotary scratch drive array chosen as the actuator, it was necessary to design a mirror that could be fabricated in plane with the motor and then assembled on top after release. The goal is to fabricate both the mirror and the motor with the same process run from a commercial fabrication service provider (MEMSCAP MUMPS® process [9]) to increase commercial viability. Two alternative designs, each offering different advantages, have been implemented to accomplish this goal.

**Pull-up Mirror**

In this design, the mirror is pulled into place on top of the rotary scratch drive array (Figure 3). Two sets of hinges are employed, one at either end of the support trusses. These hinges allow the mirror to be pulled out of plane. The pull-up mirror design allows for easy coating of the mirror surface with gold as part of the MUMPs process runs. The gold coating increases reflectivity and thus enhances the resolution and signal-to-noise ratio of the optical signals. The pull-up mirror is from the “poly1” layer in the MUMPs process, with the underlying oxide as sacrificial layer. The size of the smaller design is 592 µm × 527 µm and that of the larger one is 990 µm × 880 µm. However, coating the surface with gold may warp the mirror due to difference in thermal expansions between the gold film and the poly1 material during and after gold deposition. Therefore, the gold film thickness should be limited to the minimum to achieve sufficient reflectivity.
Flip-over Mirror
This design is moved into position by flipping up and over itself onto the rotary scratch drive array (Figure 4). The bottom-side of the mirror during fabrication and before assembly becomes the reflective surface after assembly. This mirror design does not allow for gold coating as part of the MUMPS® process. However, the advantage of this design is that the mirror surface is nearly optically flat as a direct result of the fabrication process. The “polyl” layer that the mirror is made of is deposited directly on top of a smooth silicon oxide surface. After deposition, the top surface of this polycrystalline silicon (polysilicon) layer always exhibits graininess to a varying degree, depending on the deposition temperature and other parameters. In contrast, the bottom surface in contact with the oxide layer is always smooth, independent on the deposition parameters. Another advantage in using the bottom surface as the mirror surface is that the mirror surface is protected during processing until the final release and assembly steps. In this work, the mirror design that will sit on top of the small rotary scratch drive arrays is 600 µm × 620 µm and the mirror to go on top of the large actuator design is 1000 µm × 1033 µm.

Assembly
A combination of photoresist hinges, scissor hinges, and tab locks are designed into the mirror-motor combination to allow for post-fabrication assembly (Figure 5).
Photoresist “hinges” [2] allow this device to self-assemble simply by heating. The surface tension developed in the photoresist upon melting has been demonstrated to generate enough force to rotate objects out of plane. All hinges in the flip-over mirror can utilize this principle for hands-free assembly. Also, the photoresist itself will help to hold the mirror assembly in place at a 45° angle after the assembly step. Spring locks are used to constrain the mirror to rest at this angle. The pull-up mirror consists of one set of photoresist hinges (furthest from the reflective surface) and one set of scissor hinges (that join the support frame to the reflective surface).

FUTURE WORK
In the pursuit of the highest resolution possible, a Tensile Optical Surface (TOS) mirror [10] will be implemented. The TOS mirror consists of a set of single-crystalline silicon ribs with a polysilicon membrane stretched across the ribs. It possesses the advantageous characteristics of being lightweight, rigid, and flat. Gold can also be evaporated onto its surface for increased reflectivity, and at the same time process-induced warping is minimized with the built-in tension. It has shown less than 500 nm deformation over 70% of the cross-section. The TOS mirror can be incorporated into our current design (either the pull-up or flip-over) by replacing the current mirrors with a frame designed for the TOS mirror. It is anticipated that this approach will allow imaging at resolutions exceeding what is required for an optical biopsy.

Ultimately, the entire micro mirror and motor assembly will be integrated inside the end of a catheter tip and will be powered wirelessly with inductive coils. Wireless power transmission will allow completely unobstructed path for the 360° scanning operation. A possible implementation of a wirelessly powered scratch drive has been published recently in [11].

CONCLUSION
The 360° rotational micro mirror for transmitting and sensing OCT signal described in this paper will be an indispensable tool for enabling optical biopsy of the esophagus. It will also offer potential applications for imaging other parts of the gastrointestinal tract as well as large blood vessels.

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REFERENCES