A Wide-angle Immersed MEMS Mirror and Its Application in Optical Coherence Tomography

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***Abstract*—In this paper we report a wide-angle two-axis electrothermal MEMS scanning mirror and its application in optical coherence tomography (OCT). The wide-angle scanning was achieved by combining the large scan range of the MEMS mirror and the "Snell's Window" effect. By immersing the electrothermal MEMS mirror into a mineral oil, the original 32° field of view (FOV) can be increased up to about 75°. The wide-angle immersed mirror was employed in an OCT system and 3D OCT images were successfully obtained.**

***Keywords*—MEMS mirror, MEMS in liquid, electrothermal bimorph, wide angle, OCT**

I. Introduction

OCT is an established biomedical imaging technique which is able to obtain in *vivo*, real-time cross-sectional information of biological tissues with high resolution [1]. As one featured application, OCT can be employed for internal organ imaging which can aid the early stage cancer detection, but the major challenge is to assemble the optical scan component into the endoscopic imaging probe whose size is limited to only several millimeters [2].

Electrothermal MEMS mirrors have been extensively used in the endoscopic OCT imaging probes due to their advantages of small size, large linear range, low voltage and high fill factor [2]. Though the scan range of electrothermal MEMS mirrors is large, it can be further improved according to our recent breakthrough in which an electrothermal MEMS mirror works properly in liquid and the "Snell's Window" effect is used to amplify the optical scan angle [3]. By immersing MEMS mirrors in liquid, shock resistance can also be greatly increased.

In this paper, the scanning characteristics of an immersed two-axis electrothermal MEMS mirror is presented. The enlarged scanning range of the MEMS mirror has been utilized as the lateral scanning in a time-domain OCT system, to demonstrate its capability to be employed in the endoscopic OCT imaging probes.

II. Concept of two-axis immersed MEMS mirror

An SEM of the two-axis electrothermal bimorph MEMS mirror is shown in Fig. 1. The aperture size of the mirror is 1×1 mm^2 and the device footprint is 2×2 mm^2. The initial elevation of the mirror plate is about 250 μm due to the residual stresses in the thin films of the bimorphs. The large initial elevation of the mirror plate enables the implementation of the immersing concept as the large spacing allows the mirror plate to rotate in liquid without any serious stiction problems. Due to the viscosity, most other MEMS mirrors with small gaps or relying on resonance for operation cannot work properly in liquid.

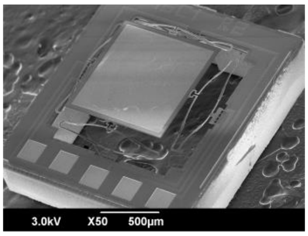

Fig. 1 An SEM of the ISC two-axis electrothermal MEMS mirror.

Four inverted-series-connected (ISC) Al/SiO$_2$ bimorph actuators [4] are connected at the middle points of the four sides of the mirror plate to provide large pure out-of-plane displacement. The four actuators can be electrically controlled separately to realize tip and tilt of the mirror plate.

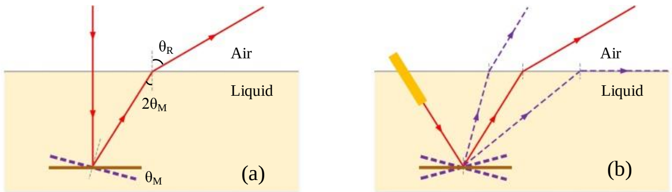

Fig. 2 Principle of "Snell Window" effect: (a) Normal incidence. (b) Oblique incidence to reach critical angle on one side.

A mineral oil is used as the liquid for the MEMS mirror to immerse as it is transparent and also has large refractive index of 1.5. The basic idea is shown in Fig. 2(a), when the mirror plate has a mechanical tilt angle θ_M, the output optical angle θ_R will becomes arcsin[n×sin(2θ_M)]. When θ_M reaches the critical angle, which is 20.9° for this oil, θ_R becomes 90° and is more than twice as much as the optical scan angle of 41.8° in air.

For the ISC MEMS mirror shown in Fig. 1, its maximum mechanical tilt angle range is ±8°. So, the mirror has a total mechanical tilt of 16°, which is smaller than the critical angle. As can be seen in Fig. 2(a), angle amplification increases when θ_M approaches the critical angle. Thus, in order to maximize the FOV, an oblique incidence is used,. As shown in Fig. 2(b), the light is incident on the mirror plate is at 25.8°. In this arrangement, the output optical beam scans the liquid/air boundary from 9.8 ° to 41.8 ° when the mirror tilts from -8 ° to +8 °. Thus theoretically the maximum output FOV reaches 75 °, which is about 2.3 times the FOV for the mirror in air.

III. Experiment Results

Care must be taken when immersing the two-axis MEMS mirror in the mineral oil. First, the packaged MEMS mirror must be wetted using a nonpolar solvent like methane. Second, the immerse MEMS mirror must be placed in a vacuum for some time to remove the air bubbles trapped in the backside chamber of the mirror plate.

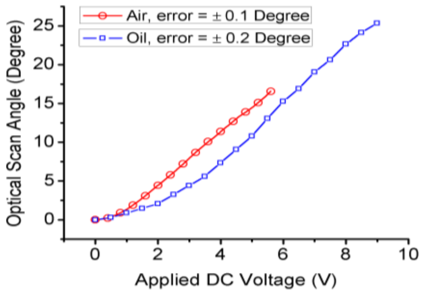

Fig. 3 Static response of the MEMS mirror in both air and liquid

The static angular tilt angle response of the MEMS mirror in air and mineral oil is shown in Fig. 3, where only one of the four actuators was excited. The maximum optical scan angle on a single side reaches 16.6 ° at 5.6 V in air and 25.4 ° at 9 V in oil. The corresponding maximum mechanical tilt angle of the mirror is 8.3 ° in both air and mineral oil.

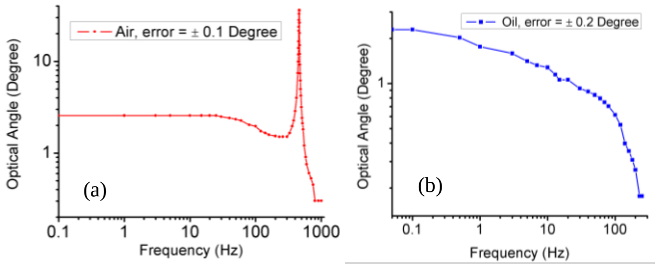

Fig. 4 Frequency responses of the MEMS mirror in both air and liquid

The frequency responses of the MEMS mirror in air and oil are measured. Fig. 4(a) shows the resonance of the MEMS mirror in air is 462 Hz. No resonance of the MEMS mirror has been observed in mineral oil due to the viscous damping. The MEMS mirror has a 3dB cutoff frequency of 3 Hz in liquid.

The setup of the immersed two-axis MEMS mirror for OCT imaging experiment is shown in Fig. 5(a), where a single mode fiber (SMF) with a GRIN lens glued on the tip was inserted in the liquid and pointed to the mirror with an angle of 25.8 ° for the maximum FOV as illustrated in Fig. 2(b). Fig. 5(b) shows a picture in which a red laser is used to visualize the enlarged optical scan angle. Note that the incident laser beam is from air.

The immersed MEMS mirror was then employed in an OCT system to perform the lateral scan for imaging a piece of paper. The details of the optics for the OCT are reported in [2]. The 2D and 3D OCT images shown in Fig. 6 were acquired with two differential ramp voltages (0-8 V) applied to the four actuators with the frequencies of 1.25 Hz and 5 mHz, respectively. For better imaging contrast, a piece of paper with high reflectance was used as the sample due to the light intensity attenuation of the liquid. The width of the 2D OCT image is 3.3 mm and the height is 2.5 mm. The 3D image was achieved by stacking 100 frames of 2D OCT images with the dimension of 3.3*3.3*2.5 mm. The obtained FOV is about 62 °. As the spot size of the output optical beam becomes quite large when θ_M approaches the critical angle, the degradation of the resolution and depth in OCT images will be further studied.

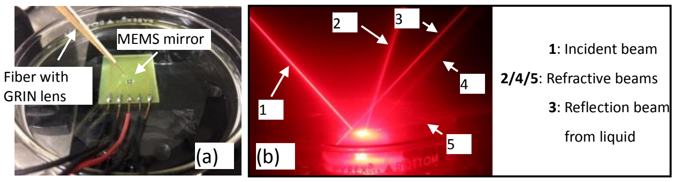

Fig. 5 Immersed ISC MEMS mirror with oblique

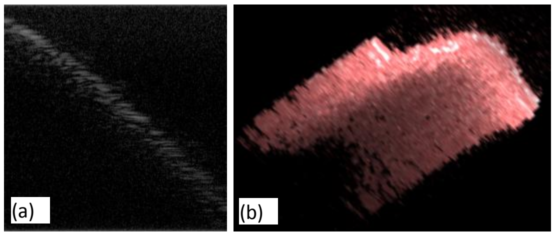

Fig. 6 (a) 2D and (b) 3D OCT images of a piece of paper

IV. Conclusion

The FOV of a two-axis electrothermal MEMS mirror has been successfully increased from 32 ° in air to 75 ° by immersing it in liquid. The scan range is enlarged by taking the advantages of Snell's window effect and the large responsivity of the electrothermal MEMS mirror at low frequency. The immersed MEMS mirror shows its capability to be used in OCT imaging system. The mineral oil works well in the 1,300 nm wavelength range. More work on the spot size increase, lateral resolution degradation, liquid absorption spectrum, packaging of MEMS endoscopic probes, and liquid filling will be investigated in the future.

Acknowledgment

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