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MEMS MIRRORS SUBMERGED IN LIQUID FOR WIDE-ANGLE SCANNING

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ABSTRACT

This paper reports an electrothermal MEMS scanning mirror working in liquid for the first time. By submerging the MEMS mirror into a mineral oil whose refractive index is 1.47, a wide-angle optical scan (>120°) was achieved at small driving voltage (<10V), and the scan frequency reached up to 30 Hz. The wide angle was achieved because of the angular increase of the "Snell's Window" effect and the large mechanical tilt angle (±18°) of the MEMS mirror as well. The power consumption is 9.9 mW/° when working in air and 11.7 mW/° in the mineral oil. This submerged optical scanner may enable many new applications of wide-angle optics.

KEYWORDS

MEMS mirror, electrothermal bimorph, submerge, mineral oil, large mechanical angle, wide-angle scanning

INTRODUCTION

MEMS mirrors have been used in a wide range of applications such as telecommunication, optical imaging, displays, and laser printers. Large mirror size, large scan range, high speed and low drive voltage are always desired but remain conflicting aims [1-3]. For instance, large scan range may be obtained only at small mirror size or at high drive voltage. Resonance scanning is often used to boost the scan range, but this requires extra control and vacuum packaging, increasing the complexity in applications such as optical switching or imaging. Even at resonance, the scan angle may be still not sufficient. For example, vision based systems may need greater than 120° viewing angle [4]. Various methods are exploited to achieve wide-angle scanning, and most of the efforts are focused on structural design or actuation optimization [5], which is subject to the mechanical limitations. Interestingly, wide field-of-view (FOV) "water camera" was demonstrated a century ago [6] by mimicking the fish eye, or using so called the "Snell's Window" effect [7] to enlarge the FOV and help break the mechanical limit. However, since then there has been little progress to directly build such a true "fish eye" device due to the poor resolution at the edge of the FOV as well as the bulky and inconvenient setup where an optical sensor needs to be immersed in liquid. In this work, we propose to immerse a small MEMS scanning mirror in liquid. By using the angular amplification, this approach can achieve large FOV for photography or large angular scan range for laser beam steering.

DEVICE CONCEPT

In this work, we utilize the "Snell's window" effect to enlarge the scan angle by submerging MEMS mirrors into a liquid whose refraction index is greater than 1. The basic idea is illustrated in Fig. 1(a), where the half output scan angle, θ_s, becomes $\arcsin[n\times\sin(2\theta_m)]$ when the MEMS mirror tilts an angle, θ_m, in the liquid (refractive index n). Fig. 1(b) plots $\theta_s \sim \theta_m$ with n=1.5 which is roughly the case for most oils. According to this plot, close to ±90° half angle, or full 180° view angle, can be achieved with only about ±21.5° mechanical tilt angle from the MEMS mirror. Thus using this submerging approach, much larger output scanning range can be achieved with the same mechanical tilt angle of the MEMS mirror. Fig. 1(c) shows the picture of a submerged MEMS mirror setup. Fig. 1(d) shows the optical beams while the MEMS mirror was scanning, where the comparison between the reflection beam in the mineral oil and the refraction beam in air clearly shows the enlarged output scan angle.

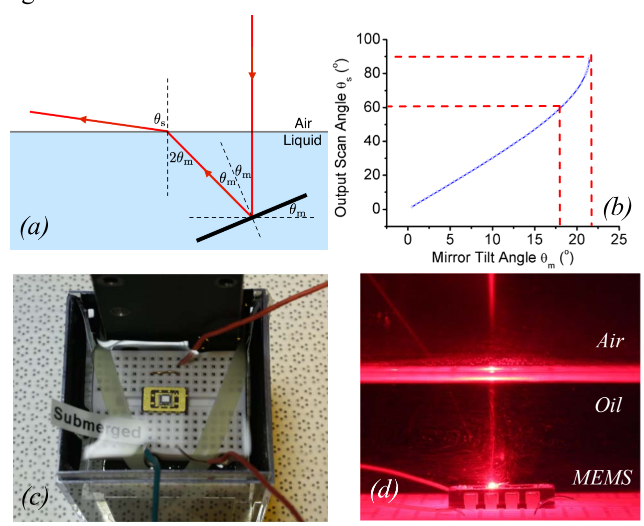

Fig. 1 (a) Principle of "Snell's window". (b) Output scan angle versus mirror tilt angle. (c) Photo of the MEMS mirror submerged in mineral oil. (d) A laser beam incident on the MEMS mirror in mineral oil.

Most MEMS mirrors are designed to work in air or vacuum and have serious problems when operating in liquid. Due to the large viscous damping, resonant-scanning electrostatic or piezoelectric mirrors may not work properly when submerged in liquid. Under non-resonant operation, piezoelectric or electrostatic mirrors may still not be able to provide sufficiently large FOV even with the "Snell's window" effect. On the other hand, an electrothermal bimorph based MEMS mirror that can perform over ±30° optical scan angle at non-resonant mode with small drive voltage has been developed [8]. This mirror is used in the setup in Fig. 1(c) and its SEM is shown in Fig. 2. The mirror plate is elevated 920 µm above the substrate due to the residual stress after device release. This large space under the mirror plate is critical for the submerging operation since it minimizes the squeeze-film damping in liquid. There are two groups of electrothermal lateral-shift-free (LSF) large vertical displacement (LVD) bimorph (Al/SiO_2) actuators [9] connected to the mirror plate, in which the three segments design of each LSF-LVD actuator cancels the lateral shift and increases the vertical displacement. Each LSF-LVD actuator group controls the vertical displacement of the corresponding side of the mirror plate. The temperature change to actuate the electrothermal LSF-LVD actuators is generated by the embedded Pt film heaters. SiO_2 thermal isolation bridges are formed between the actuators and the mirror plate to prevent the mirror plate from being heated during actuation. By applying a pair of differential voltage signals to the two actuator groups, the mirror plate will generate angular scan. The device was fabricated by a combined surface and bulk micromachining process [8]. The 1.7 mm×1.9 mm mirror plate is 40 µm thick Si coated with 1 µm Al, and the entire chip size is 3.2 mm×3.2 mm.

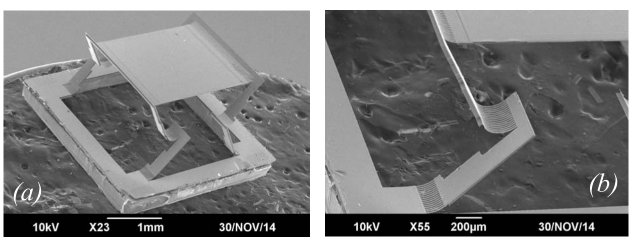

Fig. 2 (a) SEM of the electrothermal MEMS mirror. (b) Close-up view of the LSF-LVD bimorph actuator

DEVICE CHARACTERIZATION

The fabricated device was wire bonded and tested in both air and mineral oil. Vacuum treatment was performed before actuating the MEMS mirror in liquid to remove air bubbles trapped between the mirror plate and substrate which otherwise might break the mirror plate due to the temperature rise caused by the electrothermal actuation. To observe and record the scanning response, a laser beam was incident perpendicularly through a pinhole on a graph paper. The MEMS mirror in air or in liquid was placed on the other side of the graph paper with the laser beam also perpendicular to the mirror plate at zero drive voltage. The lateral shifts of the laser spot on the graph paper at various voltages were recorded and then the optical scan angles were calculated. The static responses, dynamic responses and optical transmission were measured.

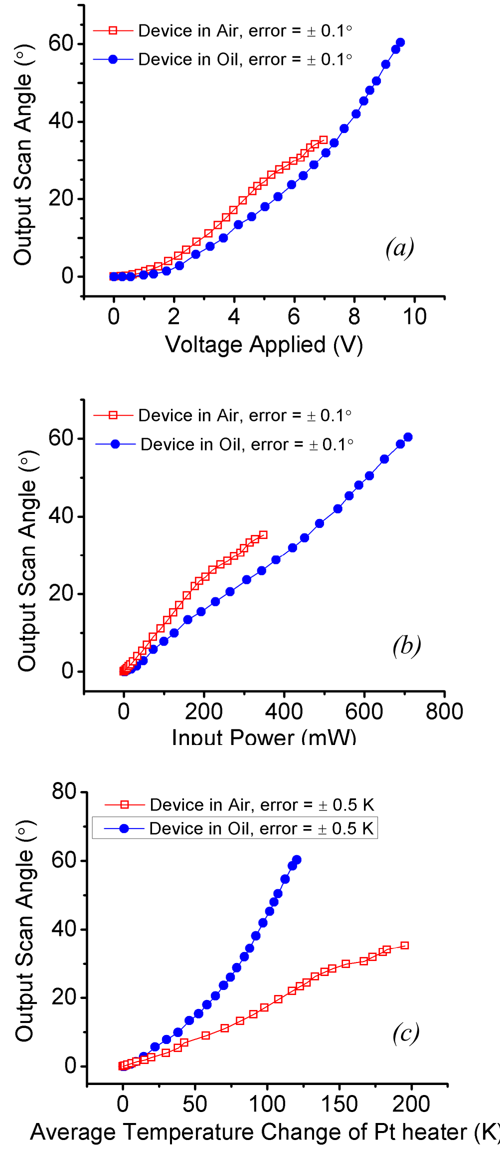

Fig. 3 Static output scan angle versus (a) voltage (b) Input power and (c) Average temperature change of the embedded Pt heater.

Static measurement results

The static angular scan response of the MEMS mirror was tested by applying a DC voltage to one of the LSF actuators. Scan angles versus applied voltage, power consumption and temperature change were measured. As shown in Fig. 3(a), the maximum scanning range is ±35.3° at 6V in air and ±60.4° at 9.5 V in the mineral oil. The corresponding maximum mechanical tilt angles of the MEMS mirror are 17.7° and 18.1°, respectively, which are very close, but the output angle for the submerging case is almost doubled, indicating that the submerging approach helps "break" the mechanical limit to achieve wider scanning range. Fig. 3(b) compares the power consumptions, which are approximately 9.9 mW/° and 11.7 mW/° for the cases in air and mineral oil, respectively, so 18% extra power is needed for each degree of tilt angle for the MEMS mirror actuated in mineral oil. The electrical resistances of the Pt heaters increase significantly with the applied voltage due to the thermal coefficient of resistivity (TCR). The TCR of the fabricated Pt heater was measured to be 0.003/K by a temperature controlled oven. By tracking the electrical resistances of the Pt heaters embedded in the LSF actuators with a known TCR, the average temperature change of the actuators can be estimated. As shown in Fig. 3(c), with the same average temperature change, much larger scanning angle is achieved in liquid than in air. The liquid can also greatly improve the shock resistance of the mirror plate.

Dynamic measurement results

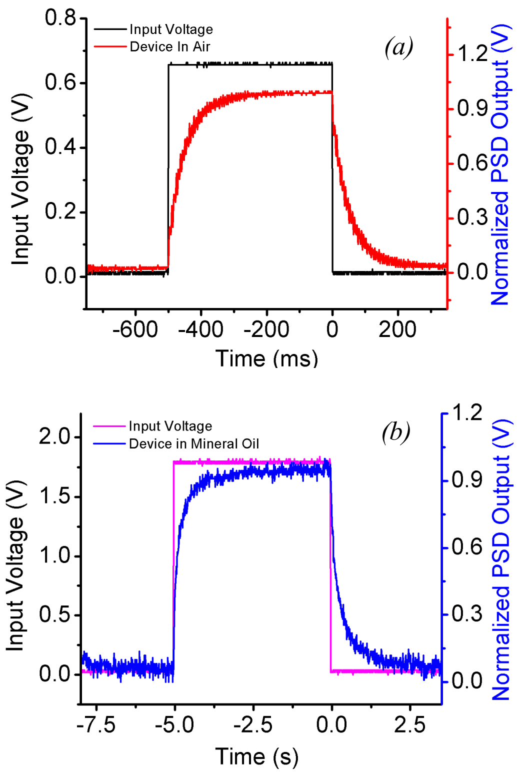

Fig. 4 Step response of the MEMS mirror: (a) In air and (b) in mineral oil.

The step responses of the MEMS mirror were measured with a photosensitive detector (PSD) monitoring the reflected beam. As plotted in Fig. 4(a), the response time in air is about 0.1 s. The response time in liquid is larger than in air, as shown in Fig. 4(b), observed to be about 1s. From Fig. 3(b) and (c), based on $\Delta T = P_E \times R_T$ it can be concluded that the equivalent thermal resistance R_T became smaller when the MEMS mirror was operating in mineral oil. Thus the increase of the thermal response time is mainly due to the additional thermal capacitance of the liquid around the bimorph area.

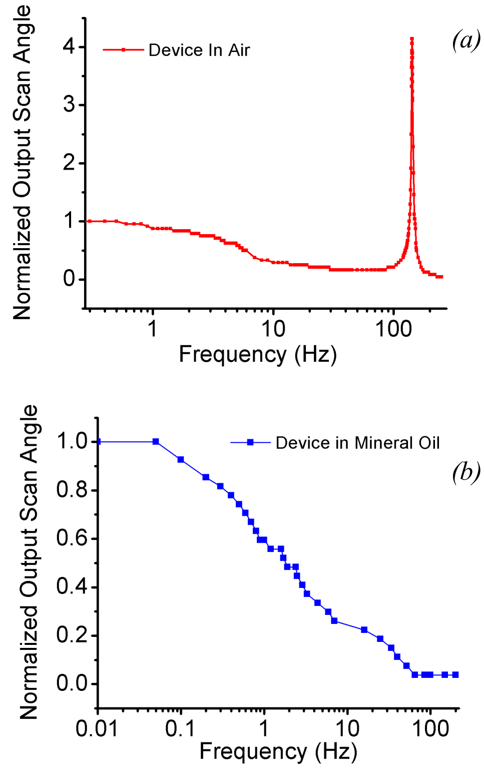

Fig. 5 Frequency response of the MEMS mirror: (a) in air and (b) in mineral oil.

The frequency responses were measured by applying a voltage of (a+bsinωt) V (in air: a=3.5 V, b=0.5 V; in mineral oil: a=5 V, b=1 V) to the LSF actuator and tracking the corresponding scanning ranges. Fig. 5(a) shows that in air the resonance of the MEMS mirror is 142 Hz. In contrast, as shown in Fig. 5(b), no resonance of the MEMS mirror is observed in liquid due to the viscous damping and the mirror can operate up to 30 Hz.

Optical measurement results

In the case of the scanning mirror submerged in liquid, the output scanning beam is the refraction from the liquid to air. According to the Fresnel equations, the transmittance is polarization-dependent. Thus the transmittances of both s- and p-polarized laser beams were measured. Fig. 6 shows the experimental results, compared to the theoretical values, indicating that p-polarized light is preferred for the submerged scanning as the transmitted power does not decrease significantly.

In addition, most of the wide-angle optical systems suffer from distortion problems [10], i.e., the laser beam size increases with increasing scan angle. Fig. 7 shows the measured spot sizes of the output scanning beam from the submerged scanning unit at different output scanning angles, where unsurprisingly the angular spot size changes from 0.5° to 0.9° when the scanning angle varies from 5° to 60°.

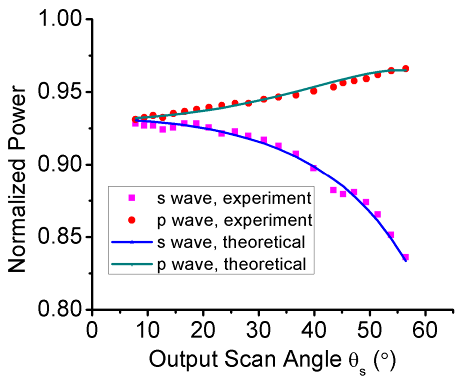

Fig. 6 Power transmission of the output scan beam

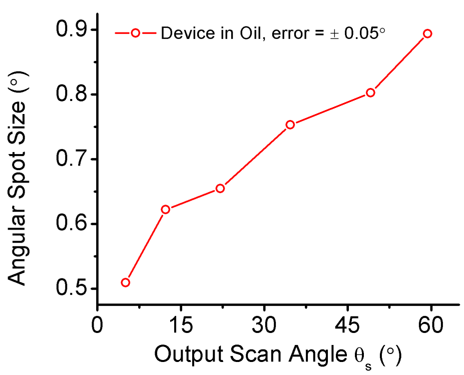

Fig. 7 Spot size of the output scan beam

CONCLUSION

A novel approach of enlarging the scanning range of MEMS mirrors by taking advantage of the “Snell’s Window” effect has been proposed and experimentally verified. Both the static and dynamic scanning have been demonstrated that the electrothermal LSF bimorph based MEMS mirror can work properly in liquid and have simultaneously achieved large scanning range up to ±60°, small driving voltage of less than 10V and fast scanning speed up to 30Hz. The optical performances have also been studied. Furthermore, with good packaging the liquid medium helps protect the MEMS mirror from external shock and improve the reliability. This submerging approach provides an easy way to achieve a compact, low cost and reliable wide-angle scanning unit.

ACKNOWLEDGEMENT

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