

Endoscopic optical coherence tomography with new MEMS mirror

Tuqiang Xie, Huikai Xie, G.K. Fedder and Yingtian Pan

A micromachined mirror to enhance the transverse scanning performance of endoscopic optical coherence tomography (EOCT) is presented. The scanning angle of the mirror can be up to 37° . The EOCT can image an area to $4.2 \times 2.8 \text{ mm}^2$ at 5 frames/s. The results demonstrate its potential for *in vivo* imaging diagnosis.

Introduction: Optical coherence tomography (OCT) is a new optical imaging technique that can provide cross-sectional images of biological tissue, highly desirable for imaging diagnosis of superficial lesions [1]. OCT can delineate tissue micro morphology, holding the potential for non-invasive optical biopsy [1, 2]. In recent years, the development of real-time, high-performance, reliable and low-cost OCT catheters and endoscopes has attracted more attention for future clinical applications [1, 2]. To miniaturise lateral scanning probes to fit into slender endoscopes, various attempts of transverse laser scanning techniques have been employed including a rotary fibre-optic joint connected to a 90° deflecting micro prism or a small galvanometric plate swinging the distal fibre tip [1, 2]. The rotary fibre joint is more suitable to image the circumference of intraluminal tracts and the galvo swinger has a limited range ($<2 \text{ mm}$) for transverse scanning [1, 2].

Microelectromechanical systems (MEMS) have found enormous applications in biomedical areas because of their small sizes, low consuming energy, nominal forces and flexibility. A recent report of endoscopic OCT (EOCT) utilising a MEMS mirror for endoscopic laser scanning has been proposed by the authors, showing great promise [3]. However, buckling of the employed bimorph mesh structure causes a $\sim 10^\circ$ discontinuity in the angular actuation curve, severely limiting the usable range of the transverse laser scanning. In this Letter, we present an improved EOCT using a modified single-crystalline silicon (SCS) micromirror which completely eliminates buckling and allows transverse scanning over 37° . Preliminary results based on animal studies are presented.

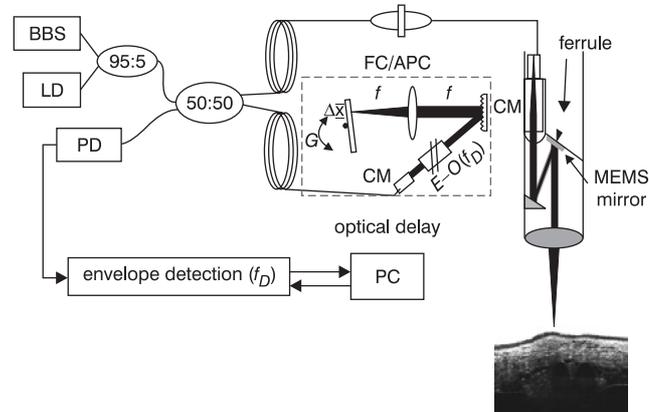


Fig. 1 Schematic diagram of EOCT with MEMS mirror

BBS: broadband light source; LD: aiming laser; PD: photodiode; CM: fibre-optic collimator

Method: Fig. 1 is the schematic diagram of the EOCT system, which is based on a fibre-optic Michelson interferometer. The light source for illumination has a pigtailed output power of 13 mW, a central wavelength of 1320 nm and spectral bandwidth of 77 nm, yielding a coherence length of $10 \mu\text{m}$. In the reference arm of the fibre-optic interferometer, the light from the fibre endface is coupled into a $\phi 2 \text{ mm}$ collimated beam by an angle-polished GRIN lens. The collimated light beam is then guided to a high-speed depth scanning unit which contains a rapid grating-based optical delay line, as has been previously reported [3]. The light in the sample arm is collimated by a custom fibre-optic spherical lens to a beam size of 0.75 mm , deflected by a conventional mirror and a transversely scanning MEMS mirror. It is then focused by an $f = 10 \text{ mm}$ scan lens onto the surface of the biological tissue and the backscattered light exiting the specimen will be collected by the same optics. The

OCT endoscope including the connection fibre and the transverse scanning optics is integrated into a standard endoscope.

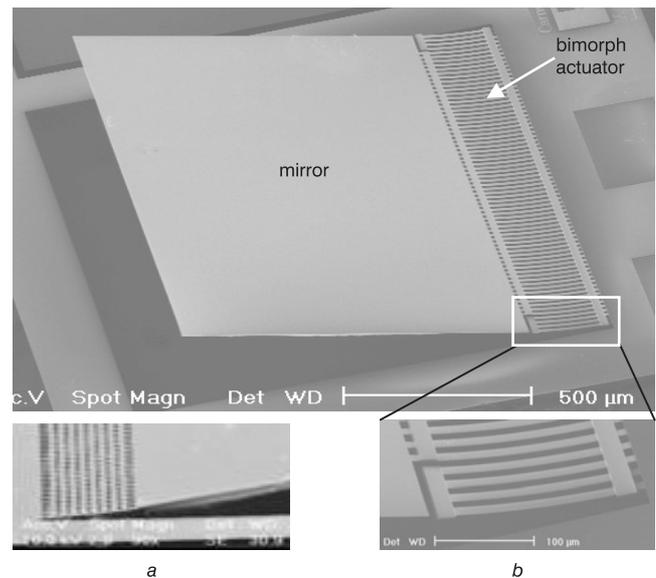


Fig. 2 Mesh of old MEMS mirror and SEM of modified MEMS mirror

a Old MEMS mirror b Modified MEMS mirror

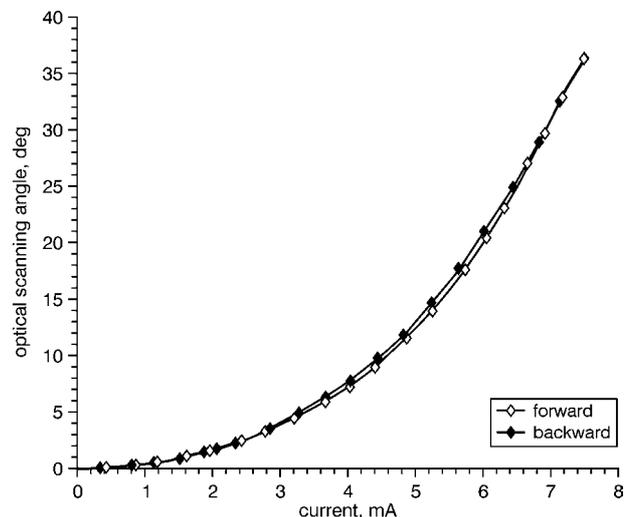


Fig. 3 Characteristic curve of MEMS mirror

To evaluate the laser scanning performance and its effect on OCT image fidelity, OCT scopes employing both old and new MEMS mirrors have been assembled and tested. Both MEMS mirrors employ a bimorph actuator with an integrated polysilicon heater to actuate an Al-coated mirror with active size of $1 \times 1 \text{ mm}$. The primary difference is the bimorph structure, which has been found crucial to the performance of MEMS angular actuation. In the old mirror the bimorph actuator is a mesh of cross-connected beams as shown in Fig. 2a [3]. The beams are composed of a $0.7 \mu\text{m}$ Al layer coated on top of a $1.2 \mu\text{m}$ SiO_2 film embedded with a $0.2 \mu\text{m}$ poly-Si layer. The mirror is a $0.7 \mu\text{m}$ Al mirror coated on the $1.2 \mu\text{m}$ SiO_2 layer of a $40 \mu\text{m}$ single-crystal Si substrate. The mesh curls up after release as a result of tensile stress in the aluminium layer and compressive residual stress in the bottom silicon dioxide layers. Although the angular actuation range can be up to 35° , wobbling and hysteresis are noticeable [4]. As wobbling occurs in the intermediate range, the usable range of the old MEMS mirror is severely limited. In our previous EOCT, wobbling was avoided by a large (9°) preset angle on the ferrule. Nevertheless, the usable scanning angle was less than 13° , limiting the wobbling-free lateral scanning to 2.9 mm or less.

Further studies have revealed that hysteresis is caused by thermal relaxation and wobbling results from buckling of the mesh beams as a result of excessive thermal stress and expansion in the transverse direction. To eliminate this adverse effect, short transverse beams in the

bimorph mesh are removed, and thus the bimorph mesh becomes a set of parallel beams as shown in Fig. 2b. Since the bimorph beams can move freely along the longitudinal direction, buckling in both transverse and longitudinal directions is eliminated. Fig. 3 shows the test result of the modified MEMS mirror with angular actuation of roughly 37°. This permits a wobbling-free lateral scan over 6.6 mm, exceeding the full range of the endoscope tube (4.3 mm). In particular, because the curve is monotonic and smooth with less than ±2% hysteretic error, linear actuation can be easily implemented by a simple nonlinear correction to allow artifact-free full range EOCT imaging.

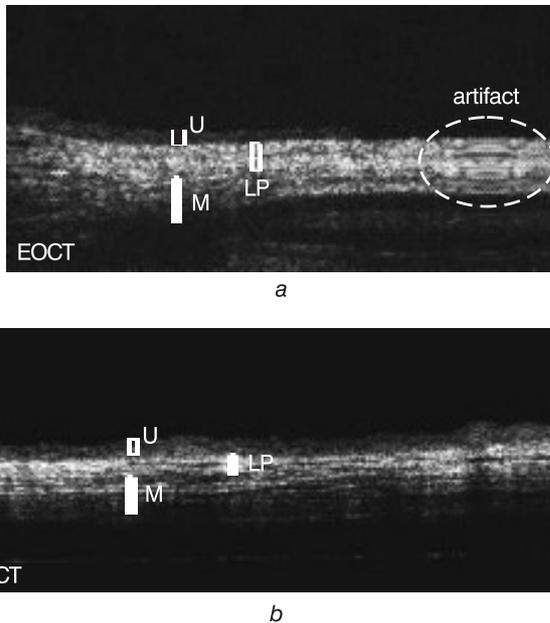


Fig. 4 Rabbit bladder imaged *ex vivo* by EOCT with old MEMS mirror and modified MEMS mirror

a With old MEMS mirror (image size $3.6 \times 2 \text{ mm}^2$)
b With modified MEMS mirror (image size $4.3 \times 2 \text{ mm}^2$)
 U: urothelium; LP: lamina propria; M: muscular layer

Results: To examine the influence of the MEMS mirrors on EOCT image fidelity, we performed a comparative image study on normal

rabbit bladders *ex vivo*. Morphological details of rabbit bladder, e.g. urothelium (U), lamina propria (LP) and muscular layer (M) can be delineated in both images as shown in Fig. 4, thus holding great promise for EOCT *in vivo* imaging diagnosis of early bladder cancers [5]. However, artifacts due to MEMS mirror wobbling are noticeable in Fig. 4a, limiting the usable lateral imaging range to be less than 2.6 mm for EOCT with the old MEMS mirror. Conversely, the image acquired with the modified MEMS mirror (Fig. 4b) is wobbling-free over the full range of the EOCT sheath (4.3 mm) at ~5 frames/s. The axial resolution of EOCT is roughly 10 μm; whereas the lateral resolution is over 20 μm (limited by φ0.6 mm fibre collimator), resulting in degraded image contrast and increased speckle noise. More importantly, the superior performance of the modified MEMS mirror suggests its applications in other laser scanning imaging techniques such as confocal and multiphoton excitation endoscopy.

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