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MEMS-Based 3D Optical Microendoscopy

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***Abstract* — Microelectromechanical systems (MEMS) devices have the advantages of small size, fast speed and low cost. MEMS-based miniature imaging probes have been developed for various optical "biopsy" imaging systems. These MEMS based optical imaging systems enable *in vivo* endoscopic optical "biopsy", resulting in a paradigm shift of optical imaging of internal organs. In particular, MEMS based endoscopic optical coherence tomography (OCT) imaging, nonlinear optical imaging and confocal imaging will be discussed.**

I. Introduction

It is still a grand challenge to detect diseases such as cancers at their early stages. Over 7 million people die of cancer worldwide each year. The high cancer mortality is mainly due to the lack of early cancer detection modalities especially for internal organs. CT, MRI and ultrasound imaging are commonly used diagnosis tools but they have issues of relatively low resolution, low contrast, radiation risk, or high cost. These imaging modalities typically provide resolutions of 0.1 mm to 1 mm. In contrast, several optical imaging techniques, such as confocal, multiphoton and nonlinear optical (NLO) microscopy, and optical coherence tomography (OCT) [1], provide much higher resolutions. Confocal and NLO microscopy can obtain submicron resolutions while OCT's resolutions range from 1μm to 15μm depending on the light sources employed. These high resolutions are achieved by spatial gating of a pinhole for confocal microscopy, spectral gating of harmonic generation or multiphoton absorption for NLO imaging, and coherence gating for OCT. With such cellular or even sub-cellular resolutions, early cancers can be detected.

Most cancers are originated from internal organs. Due to the small imaging depth (less than 3 mm) of these advanced optical imaging techniques, biopsy is needed for internal cancer diagnosis. However, cancers at the early stage do not have much visible evidence. Thus, such biopsy is often random and negative. Biopsy also introduces high risks, such as trauma.

To fully utilize the capabilities of these advanced optical imaging techniques and realize real-time, *in vivo*, minimally invasive imaging for early internal cancer detection, miniature endoscopic probes with active optical scanning engines must be developed. Optical scanning includes axial linear scanning and transverse rotational scanning.

High-resolution endoscopic imaging is very challenging since fast imaging scanning must be realized in a very small imaging probe. The most critical part in an endoscopic imaging probe is the transverse light beam scanning. Some slow but simple transverse scanning mechanisms have been reported, such as rotating a fiber micro-prism module at the proximal end [2], swinging the distal fiber tip by a galvanometric plate [3], or using a pair of scanning GRIN lenses with proper angle cut [4]. In order to increase the scanning speed, the fiber tip may be excited to its resonance by a piezoelectric tube [5]. But swinging the distal fiber tip will cause coupling loss and non-uniformity.

Micro-electromechanical (MEMS) devices are small and fast, and can be used for transverse scanning and dynamic focus tuning. High-resolution endoscopic imaging based on MEMS micromirrors and microlenses is discussed in the following section.

II. Miniature Endoscopic Probes

Most of MEMS micromirrors are surface micromachined. However, for biomedical imaging applications, relatively large mirrors (>0.5mm) are required. Therefore, bulk-micromachining processes are often used to make large, flat single-crystal silicon (SCS) based micromirrors.

Micromirrors can be actuated electrothermally, electrostatically, piezoelectrically or electromagnetically. Among these actuation methods, electrostatic actuation is the most popular because of its low-power consumption and fast response. Various electrostatic vertical comb drive designs with large mirror sizes and large rotation angles have been reported. However, high drive voltages are often required. Electromagnetic actuators can generate both attractive and repulsive forces, but they require external magnets. So packaging is an issue when the size requirement is very stringent for endoscopic imaging applications. Piezoelectric actuators have low power consumption and high speed, but piezoelectric actuation typically has small displacements, charge leakage problems, and hysteresis effects which often require a feedback control loop. Electrothermal actuation can generate large displacements at low drive voltages.

All these types of micromirrors have been applied to endoscopic optical "biopsy" imaging.

A. OCT Microendoscopic Imaging

The first MEMS endoscopic OCT imaging was demonstrated in 2001 using a 1D electrothermal MEMS micromirror [6]. After that, many research groups explored this concept using electrostatic, electrothermal or electromagnetic MEMS mirrors [7]-[12]. Most of the MEMS

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mirrors are capable of 2D scanning. The outer diameters of the OCT probes range from 2.6 mm to 8 mm.

Fig. 1(a) shows a MEMS-OCT probe with an outer diameter of 5.8 mm [12]. The MEMS mirror packaged inside the probe is shown in Fig. 1(b), which has a mirror plate size of 1mm by 1mm and can scan ±30° at 8Vdc. A 3D OCT image of a human finger obtained using the MEMS probe is shown in Fig. 1(b), which is 2.3mm × 2.3mm ×1.6 mm.

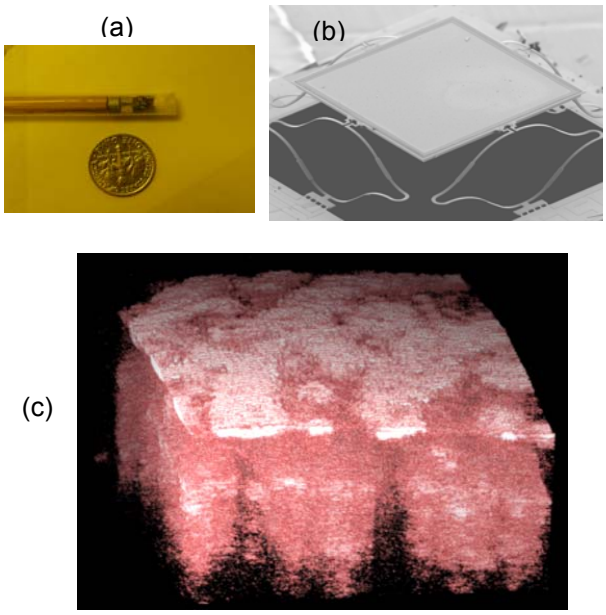

Fig. 1. 3D OCT image acquired by a MEMS probe.

B. Confocal Microendoscopic Imaging

The imaging depth of confocal microscopy is about 300μm deep in biological tissues. This requires a tuning range of about 400μm in air. The large-vertical-displacement (LVD) electrothermal bimorph actuator design developed at the University of Florida is capable of moving vertically up to 700μm. As shown in Fig. 2, such an LVD microlens is packaged into a small probe (5mm outer diameter) [13].

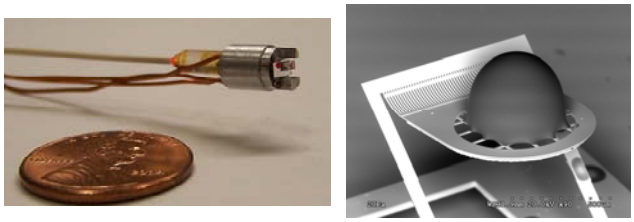

Fig. 2 Confocal imaging probe with a tunable MEMS lens.

Confocal microscopy with a fixed lens but a MEMS mirror for lateral scanning has also been reported [14][15]. In this case, the depth scan is obtained by precisely moving a stage or the entire probe. Lateral resolutions of about 0.9μm have been achieved.

C. Nonlinear Optical endoscopic imaging

Due to the doubled or tripled frequency of the generated signal, endoscopic nonlinear optical microscopy (NLOM) requires special optical fibers that can efficiently handle both wavelengths. MEMS NLOM has been reported by using a double cladding photonic crystal fiber (DCPCF) [16][17].

III. Summary

MEMS technology provides a viable solution and extends high-resolution 3D optical imaging into internal organs. *In vivo* 3D endoscopic imaging has been demonstrated by several research groups. Electrothermal actuation exhibits the best overall performance. Electromagnetic and piezoelectric actuation are also promising. Electrostatic actuation may apply to some applications too. With co-development of MEMS and probe design, *in vivo* 3D microendoscopy for early cancer detection and surgery will soon be clinically available.

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