

A 3D scanning laser endoscope architecture utilizing a circular piezoelectric membrane

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ABSTRACT

A piezo-scanning fiber endoscopic device architecture is proposed for 3D imaging or ablation. The endoscopic device consists of a piezoelectric membrane that is placed perpendicular to the optical axis, a fiber optic cable that extends out from and actuated by the piezoelectric membrane, and one or multiple lenses for beam delivery and collection. Unlike its counterparts that utilize piezoelectric cylinders for fiber actuation, the proposed architecture offers quasi-static actuation in the axial direction along with resonant actuation in the lateral directions forming a 3D scanning pattern, allowing adjustment of the focus plane. The actuation of the four-quadrant piezoelectric membrane involves driving of two orthogonal electrodes with AC signals for lateral scanning, while simultaneously driving all electrodes for axial scanning and focus adjustment. We have characterized piezoelectric membranes (5–15mm diameter) with varying sizes to monitor axial displacement behavior with respect to applied DC voltage. We also demonstrate simultaneous lateral and axial actuation on a resolution target, and observe the change of lateral resolution on a selected plane through performing 1D cross-sectional images, as an indicator of focal shift through axial actuation. Based on experimental results, we identify the optical and geometrical parameters for optimal 3D imaging of tissue samples. Our findings reveal that a simple piezoelectric membrane, having comparable dimensions and drive voltage requirement with off-the-shelf MEMS scanner chips, offers tissue epithelial imaging with sub-cellular resolution

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1. Introduction

With their compact geometry and simple architecture, piezo-scanning based fiber probes have been widely utilized in various optical imaging modalities, such as confocal imaging [1], optical coherence tomography [2], and multiphoton [3], imaging. The form factor of a piezo-scanning probe enables accessing tissue sites that are difficult to reach, while providing high-resolution images that reveal pathological details. Coupled with ultrafast lasers, piezo-scanning fiber probes have also been applied in microsurgical applications [4,5].

In a piezo-scanning fiber probe, light is mapped onto the tissue that is exiting the extended optical fiber, which is encircled by and actuated with a cylindrical piezoelectric tube actuator (Fig. 1(a)). The piezoelectric tube, which converts applied voltage to mechanical movement, is driven at the mechanical resonance of the extended fiber to create the desired scan pattern. Owing to the four quadrant electrodes surrounding the piezo-tube, various 2D tissue scan patterns (spiral or Lissajous patterns) can be achieved for imaging and microsurgery.

Axial scan capability is essential in a confocal optical imaging system for imaging tissue sections at various depths, rendering 3D tissue blocks from imaged slices or to perform ablation within a 3D volume. Current piezo-scanning fiber devices alone typically only utilize lateral scanning, thus are limited to imaging/ablating a single depth plane to form a 2D FOV. To overcome the axial scan limitation that is inherent in the piezo-scanned fiber probes, tissue samples are commonly placed on micromanipulators to address different planes in a laboratory setting [6]. However, clinical procedures would necessitate an internal mechanism within the probe for enabling axial scan through the tissue. Vocal fold scarring [6] and fibrosis that occurs in the liver [7] are among the applications that require 3D scanning of the tissue in order to precisely locate the collagen-rich regions, before their treatment.

Towards developing miniaturized tools with focus adjustment capability for 3D tissue imaging, extensive work has been showcased in literature. Separate MEMS scanners for lateral (2D scanner) and axial directions (1D scanner) were introduced, where a microlens was

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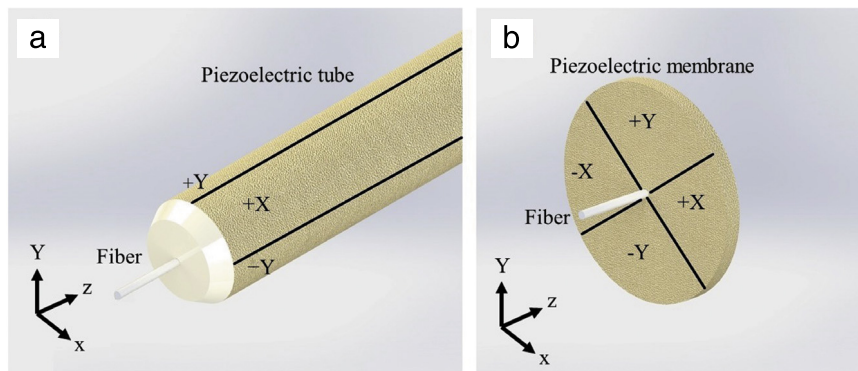


Fig. 1. Piezo scanning fiber endoscopy: (a) conventional fiber scanning architecture utilizing quadrant electrode piezoelectric cylinder (b) Proposed piezo-membrane based endoscopic architecture for 3D imaging/ablation.

mounted on the axial scanner for focus adjustment to acquire 3D confocal reflectance images [8]. Multiple MEMS chips have also been integrated with a VCSEL laser, which enables transmissive scanning of the light beam. In this configuration one MEMS chip is dedicated for lateral scanning of a microlens, meanwhile the other MEMS chip is dedicated for the axial scan of another microlens, combination of which leads to 3D steering of the beam within the tissue [9].

In an effort to develop a single micromachined device to scan in 3D, MEMS scanners were manufactured, having three degrees of freedom, for use in dual axes confocal imaging application [10]. Yet in another study, three fibers were integrated with a piezoelectric fiber scanner, where the fibers were intentionally placed with axial offset to address three different planes within the tissue [11]. Yet in another study, a piezoelectric fiber scanner was combined with a shape memory alloy, to extend the 2D scanning capability of the piezo-scanner into 3D [12]. In all of the mentioned strategies either an additional mechanism is integrated with the 2D lateral scanning mechanism (a piezoelectric fiber or a MEMS scanner), or a solution is proposed to address discrete number of axial planes only. Furthermore, proposed MEMS systems that are capable of 3D scanning bring significant challenges, having 6+ lithography masks included in their fabrication process.

Here, a piezo-scanning endoscopic architecture is proposed for 3D imaging or ablation. The proposed device simply utilizes a piezoelectric membrane that is placed perpendicular to the optical axis and a fiber optic cable that extends out from and is actuated by the membrane, as illustrated in Fig. 1(b). The circular membrane is divided into four electrically isolated parts to form quadrant electrodes (check experiment part for details). One or multiple lenses may be utilized for beam delivery and collection. Unlike its counterparts that exploit piezoelectric cylinders, the proposed architecture offers quasi-static actuation capability in the axial direction along with the resonant actuation in lateral directions, owing to the compliant nature of the membrane along the optical axis. On the contrary, a piezoelectric cylinder is relatively stiff along the optical axis, requiring extremely high voltages for its elongation. The extended fiber geometry determines its mechanical resonance in the lateral direction while the movement in the axial direction is achieved through applying a DC signal to all electrodes simultaneously. Our results show that membrane based piezoelectric 3D scanner is capable of providing tissue epithelial imaging with sub-cellular resolution while having comparable dimensions and drive voltage requirement with off-the-shelf MEMS scanner chips. The endoscopic architecture that is capable of cellular level epithelial tissue imaging can be used for diagnosis of many diseases like carcinomas of the internal organs.

2. Electrode driving scheme for simultaneous lateral and axial scanning

The electrode drive scheme is illustrated in Fig. 2(a) and (b). Simultaneous lateral (resonant) and axial (quasi-static) drive requires

simultaneous application of AC and DC voltages onto the electrodes. In a biaxial drive scheme (Fig. 2(a)), all electrodes are driven at the resonance frequency of the extended fiber cable in the corresponding direction. In this scheme, upon applying a constant frequency to all electrodes with 90° of phase difference among neighboring electrodes results in a spiral scan pattern [13], whereas applying slightly different frequencies to orthogonal electrodes results in a Lissajous pattern [4]. Spiral and Lissajous scan patterns have been extensively compared in literature [14,15] in terms of coverage uniformity and frame rate, and have been preferred one over the other for different applications. For both spiral and Lissajous scan pattern that address the lateral plane, addition of a DC signal on all electrodes results in out-of-plane bending of the membrane, which will cause an axial motion and thus a focus shift at the targeted plane. The biaxial drive scheme can be modified to produce a uniaxial drive scheme (Fig. 2(b)), such that only two ($+X$ and $+Y$) out of four ($\pm X$ and $\pm Y$) electrodes are driven with an AC signal, while a DC signal is applied to all four quadrants. The uniaxial drive scheme is more preferable due to its simpler control electronics.

3. Characterization

3.1. Experimental setup

An optomechanical setup was constructed to test axial actuation capability of various quadrant electrode piezoelectric bimorph membranes (250 μm thick 5, 10, 15 mm diameter), as illustrated in Fig. 3. Within the setup, the laser source (Thorlabs CPS196: 1 mW power, 630 nm wavelength) is coupled into a single mode fiber (Thorlabs SM600) using a 0.17 Numerical Aperture (NA) objective lens. A transparency mask having a cross shape was printed to determine and execute incision (of $\sim 100 \mu\text{m}$ depth) of the isolation lines on the piezoelectric membrane (25-mm diameter) to form quadrant electrodes. Once the electrodes were defined, a hole having 150 μm diameter was through-hole drilled at the center of the membrane. Then, a stripped single mode fiber having 125 μm diameter and 10 mm extended length was inserted, and stabilized with epoxy. It is noteworthy to mention that the extended length determines the resonance of the extended fiber optic cable, and can be adjusted to a specific value to meet speed and field-of-view (FOV) requirements. Various sizes of rings (Fig. 2(a)) were manufactured on a printed circuit board (PCB) to be placed on the membrane for both adjusting the effective diameter of the freely moving part of the membrane to 5–15-mm and also to apply the drive voltages to the membrane, annihilating the necessity to attach wires to the dynamic portion of the membrane. In a practical scenario, wire-bonding can also be performed on the membrane to apply necessary voltages without affecting the dynamic behavior. The tip of the extended fiber optic cable was mapped onto a USAF resolution target (Thorlabs R1DS1N) through the use of two back-to-back 0.65NA objective lenses, with one-to-one imaging condition. The observed resolution pattern, and the effect of

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