Two-Dimensional Endoscopic MEMS Scanner for High Resolution Optical Coherence Tomography

W. Piyawattanametha, L. Fan, S. Hsu, M. Fujino, M. C. Wu
Department of Electrical Engineering, Integrated Photonics Laboratory
University of California Los Angles, Los Angeles, CA 90095, USA

P. R. Herz, A. D. Aguirre, Y. Chen, J. G. Fujimoto
Department of Electrical Engineering and Computer Science and Research Laboratory of Electronics
Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Abstract: High resolution OCT is demonstrated with a novel two-dimensional MEMS scanner employing comb-drive actuation. Imaging is demonstrated with a Cr^{4+}:Forsterite laser and high-speed scanning to achieve ~5 um axial resolution at up to 20 frames/sec.

© 2004 Optical Society of America
OCIS codes: (170.4500) Optical coherence tomography; (170.3880) Medical and biological imaging

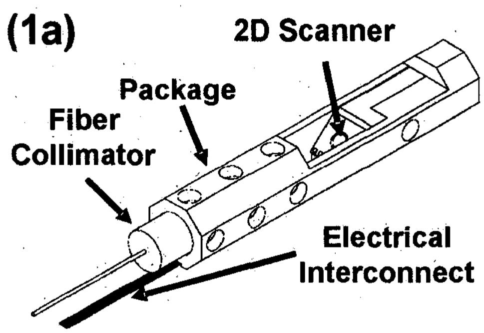
1. Introduction

Optical coherence tomography (OCT) is an emerging technology for high-resolution endoscopic imaging of biological tissues *in situ* and in real time [1]. Endoscopic OCT can distinguish architectural layers *in vivo* and can differentiate normal from tumor lesions within the human gastrointestinal tract. A need for compact, robust scanning devices for endoscopic applications has fueled the development of MEMS scanning mirrors for confocal imaging [2, 3] and for optical coherence tomography [4, 5]. Demonstrations of MEMS scanning OCT endoscopes to date, however, have been limited to single-axis scanning.

In this paper, we report the use of a two-dimensional (2D) MEMS based endoscopic scanner for OCT imaging. The device package of ~6-mm diameter is compatible with requirements for minimally invasive endoscopic procedures. A modelocked Cr^{4+}: Forsterite laser centered at 1250 nm with ~ 180-nm bandwidth is used to achieve 5-um axial resolutions. *In vivo* images of the human dermis and nail fold region are acquired at up to 20 frames per second.

2. Methods

Figure 1a shows a schematic of the fiber-coupled MEMS scanning endoscope. The compact aluminum housing can be machined for low cost and allows precise adjustment of optical alignment using tiny set screws. The optics consist of a graded-index fiber collimator followed by an anti-reflection coated achromatic focusing lens producing a beam diameter (2w) of ~ 13 um.



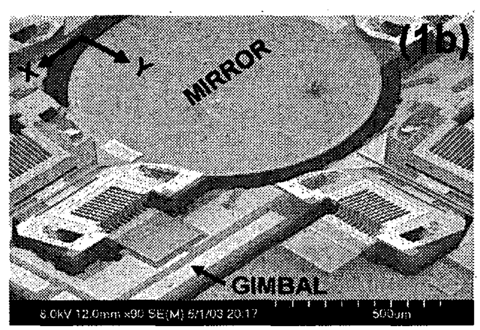


Figure 1. (a) Photograph and schematic of endoscopic MEMS package. The package was 6 mm diameter and can be further reduces in size. (b) SEM of the 2D scanner.

The 2D MEMS scanner is mounted at 45 degrees and directs the beam orthogonal to the endoscope axis in a side-scanning configuration similar to those typically used for endoscopic OCT procedures. Post-objective scanning eliminates off-axis optical aberration encountered with pre-objective scanning. Figure 1b shows a scanning electron micrograph of the device. The large 1-mm diameter mirror allows high-numerical-aperture focusing while the angled vertical comb (AVC) actuator provides high-angle scanning at low applied voltage [6]. The actuator utilizes torsion beams and a gimbal-mounting configuration to scan the MEMS mirror on two axes. A sawtooth drive waveform of 30-70 volts was used to scan the mirror at frequencies up to 20 Hz for imaging.

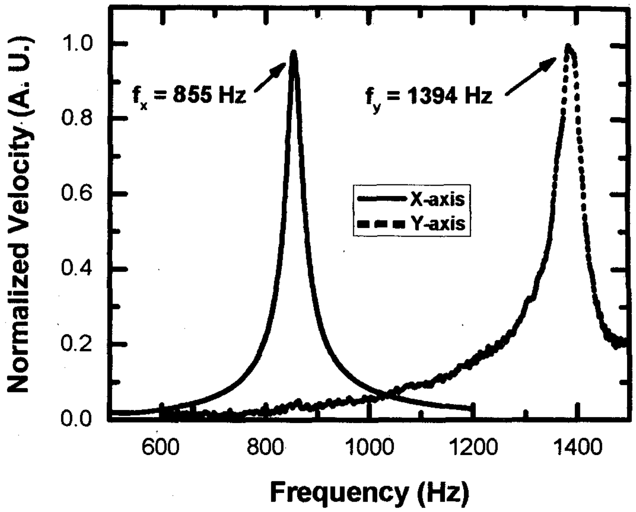


Figure 2. Frequency response of the two-dimensional MEMS scanner. High-speed resonant scanning should enable endoscopic microscopy applications.

The 2D MEMS scanner can also be used for endoscopic microscopy applications by using fast-axis resonant scanning. Figure 2 shows the frequency response for the mirror. High-frequency scan rates up to 1.4 kHz are possible, which should enable real-time microscopy applications.

3. Results

Figure 3a shows an *in vivo* OCT image of human skin. The axial resolution was ~5 um in air, corresponding to ~4 um in tissue. The transverse resolution was 13 um. The stratum corneum, epidermis layer, and a spiraling sweat duct are visualized. Figure 3b shows an image of the human nailfold. Good delineation of nailfold structure can be seen with low image speckle. Acquisition rates ranging from 2 Hz (1000 transverse pixels per image) to 20 Hz (160 transverse pixels per image) were demonstrated. Fast acquisition rates enabled real-time video capture and frame averaging to improve image contrast. These results are preliminary and were obtained with uncoated mirror optics. Further improvement in sensitivity should be possible with the next generation of devices in process.

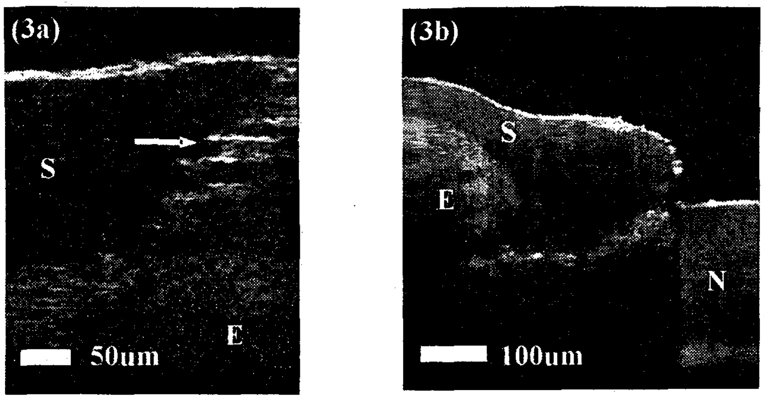


Figure 3. OCT images obtained with the MEMS scanner. (a) *In vivo* image of human skin showing delineation of stratum corneum (S), epidermis (E), and a spiraling sweat duct (horizontal arrow). (b) Image of human nail fold obtained at 20 frames per second with 4 frame averaging, with stratum corneum (S), epidermis (E), and nail (N) clearly delineated.

4. Conclusion

High-resolution, *in vivo* OCT imaging with an endoscopic two-dimensional MEMS scanner is demonstrated with 5-um axial resolution. Such 2D scanning devices have exciting promise for three-dimensional endoscopic OCT imaging. Using high-speed resonant scanning, these devices also promise to enable endoscopic optical coherence microscopy and multiphoton microscopy [7, 8].

5. References

1. Tearney, G.J., M.E. Brezinski, B.E. Bouma, S.A. Boppart, C. Pitvis, J.F. Southern, and J.G. Fujimoto, *In vivo endoscopic optical biopsy with optical coherence tomography.* Science, 1997. **276**(5321): p. 2037-9.
2. Dickensheets, D.L. and G.S. Kino, *Micromachined scanning confocal optical microscope.* Optics Letters, 1996. **21**(10): p. 764-766.
3. Piyawattanametha, W., H. Toshiyoshi, L. LaCosse, and M.C. Wu. *Surface-micromachined confocal scanning optical microscope.* in *Conference on Lasers and Electro-Optics (CLEO 2000). Technical Digest. Postconference Edition. TOPS Vol. 39.* 2000. San Francisco, CA, USA: Opt. Soc. America.
4. Pan, Y., H. Xie, and G.K. Fedder, *Endoscopic optical coherence tomography based on a microelectromechanical mirror.* Optics Letters, 2001. **26**(24): p. 1966-8.
5. Zara, J.M., S. Yazdanfar, K.D. Rao, J.A. Izatt, and S.W. Smith, *Electrostatic micromachine scanning mirror for optical coherence tomography.* Optics letters, 2003. **28**(8): p. 628-30.
6. Piyawattanametha, W., P.R. Patterson, D. Hah, H. Toshiyoshi, and M.C. Wu. *A 2D scanner by surface and bulk micromachined angular vertical comb actuators.* in *OMEMS 2003, IEEE/LEOS Int. Conf. on Optical MEMS.* 2003. HI, USA.
7. Aguirre, A.D., P. Hsiung, T.H. Ko, I. Hartl, and J.G. Fujimoto, *High-resolution optical coherence microscopy for high-speed, in vivo cellular imaging.* Opt Lett, 2003. **28**(21): p. 2064-6.
8. Jung, J. and M.J. Schnitzer, *Multiphoton endoscopy.* Optics Letters, 2003. **28**(11): p. 902-904.