Optically-modulated MEMS Scanning Endoscope for Optical Coherence Tomography

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Abstract: This paper presents a novel configuration of a MEMS scanning endoscope that is actuated by external optical modulation. Light at a wavelength in the 1550nm range is used to modulate a scanning MEMS mirror, and wavelength of 1310nm, commonly used for optical coherence tomography (OCT), is used for the probe beam. This novel approach provides for the operation of a scanning endoscope without the need for directly powering up the scanning element, in this way a less hazardous apparatus for in-vivo diagnosis is possible. A fabricated module is demonstrated in which a MEMS mirror scans at the resonant frequency of 350Hz generating a optical scanning angle of 8degrees.

OCIS codes: 230.3990 Microstructure devices, 230.5160 Photodetectors, 110.4500 Optical Coherence Tomography, 170.2150 Endoscopic imaging

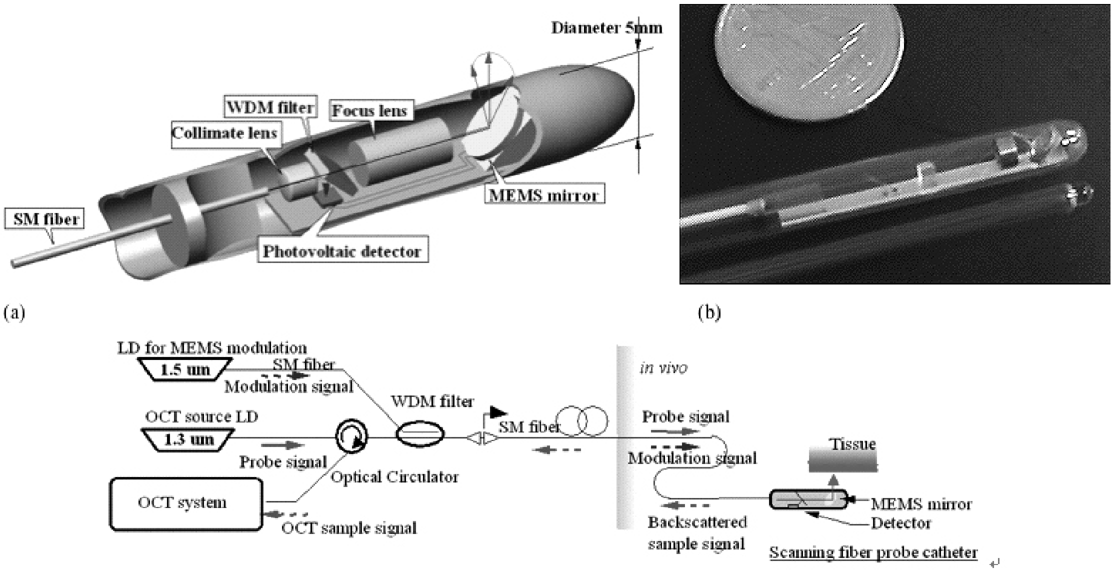
1. INTRODUCTION

The scanning fiber-optic catheter technique is a next step to introduce optical coherence tomography (OCT) to endoscopic applications such as diagnosing a gastrointestinal tact or monitoring plaque in the vascular vein[1,2,3]. Amongst the various technologies that facilitate the scanning of an optical beam for use in endoscopic procedures it is MEMS-base catheters that have many advantages in size, speed, accuracy, and repeatability over the conventional scanning techniques that requires the whole fiber endoscope to be mechanically rotated or translated with respect to the tissue [4,5]. Previously, relatively higher voltage supply is required to deflect the electrostatic MEMS mirror to a sufficiently large angle to cover a wide imaging area. However, high voltage electricity is hazardous for in vivo diagnosis, and modulation of electricity itself may even create electro-magnetic interference (EMI) to the other medical apparatus during the operation. In this paper, an endoscope with a low voltage driven MEMS scanner and photovoltaic detector is proposed. Modulation of the MEMS scanning mirror is achieved using an optical modulation, thereby eliminating the need for electrical supply and wiring within the endoscope.

2. PRINCIPLE AND DESIGN

2.1 Concept of Optically modulated MEMS endoscope

The proposed MEMS scanning endoscope consists of a pair of lenses, a WDM bandpass filter, a photovoltaic detector, and a MEMS scanning mirror packaged in a cylindrical tube as shown in figure 1. The Photovoltaic detector and MEMS mirror are mounted on a submount and connected electrically. Two light signals at different wavelength ranges are combined with a WDM combiner filter, launched into a single mode fiber and transmitted to the endoscope. The two signals are; incoming optical probe light from an OCT light source at 1310nm and the externally coupled modulation signal at 1550nm. After collimation by a first lens, the modulation signal at 1550nm is reflected by a WDM bandpass filter to the photovoltaic detector and converted to voltage that activates the MEMS scanning mirror. The probe light at 1310nm passes through the WDM filter and propagates through a second focusing lens to the MEMS scanning mirror. The WDM filter in this case is a low pass type, having 1260-1360nm passband and 1550nm reflection band with isolation of over 30dB in 20 to 45degree tilt with respect to the optical axis. After transmission through the WDM filter, a lens of 4mm focal length focuses the collimated 1310nm signal. The Gaussian beam size before focusing is 400mm, the focused spot size is 20mm. The working distance of the lens (3.26 mm) was chosen to focus the beam at the endoscope tube circumference (5 mm diameter) after deflection by the MEMS mirror, in this way the endoscope is optimized for inspection of samples in touch with the observation window. Here, commercially available Pyrex capillary tube is used for the package for convenience. The MEMS mirror is placed right after the lens to reflect the light to the direction perpendicular to the optical axis. When actuated the MEMS mirror scans the 1310nm beam in the radial direction with respect to z-axis in order to image the cross sectional of cylindrical organs such as veins or gastro intestines using the OCT technique. If the mirror is place in 45degree tilt, optical scanning angle is 1.4 times the mechanical tilt of the mirror. In this study the target optical scanning angle was set to 10degree, so the required mechanical tilt of MEMS mirror is about 7degree.



(a)

(b)

(c)

Figure 1. (a) Configuration of optically-modulated MEMS scanning endoscope and (b)Photograph of the prototype sample, (c) Concept of system configuration

2.2 MEMS scanning mirror

The MEMS scanning mirror for this module is a single axis scanner and has angular vertical comb (AVC) actuators, that provide a large mechanical tilt angle for low voltage bias [6,7]. Figure 2 shows a photograph of the MEMS mirror. The device is made of SOI (30mm silicon/ 2mm oxide/ 400mm silicon substrate). AVC is formed in a single mask process on the device layer of an SOI wafer. Initial angle offset of movable comb tooth with respect to the stationary comb tooth is realized by so called self-assembly process utilizing in-process stiction in the drying phase after the wet sacrificial etching of the membrane as shown in figure 3 [8]. The stiction pad buckles down to the handle wafer after the sacrificial etching process and is held permanently in place by molecular binding force. This bucking action of the pad introduces the twist of torsion on the hinge that is connected to the stiction pad, and a initial angular offset of the mirror is set as a result. Compared to the other techniques for introducing an offset angle in vertical comb actuators, such as those involving complicated two photolithography and deep dry etching process, our approach only needs one mask for definition of AVC and thus is a robust process through which high device yields are possible. The MEMS mirror is designed to operate in resonant mode since the probe allowing it to repeatedly scan over a large scan angle at a constant frequency corresponding to the image-acquisition rate. The MEMS mirror has dimensions of 1mm wide, 2mm long in the direction parallel to the optical axis. MEMS mirror actuation is driven with a bias voltage between 0 to +5V at the resonant frequency of 350Hz. For applications such as OCT a slower rate, close to video rate, is desirable for lateral scanning of sample while axial scanning it is advantageous scan as fast as possible.

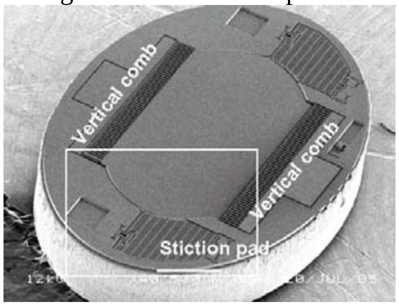


Figure 2. SEM photograph of MEMS mirror sample

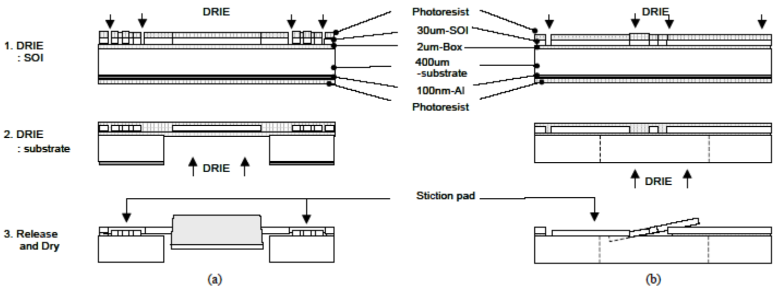


Figure 3. Fabrication process of MEMS mirror in two orthogonal cross sections

2.3 Photovoltaic detector

The photovoltaic detector used in this study is based on an asymmetric d-doped superlattice structure is used.[9] The open circuit voltage generated by a single photovoltaic detector is about 5V at input power of 7mW at wavelength of 1550nm where the input beam diameter was about 400mm. The response time of the detector at 1KHz modulation is about 50msec for rise time, about 200msec for fall time, which is sufficiently fast and high extinction ratio to achieve several hundreds Hz of scan rate. Relatively fast response in comparison with conventional photovoltaic detector attributes to he small diameter of the detector aperture of 30-40mm.

3. Results and discussion

Resonant frequency of MEMS scanning mirror was measured by laser doppler velocimeter. The first order resonance was found at frequency of around 350Hz. By operating the mirror in resonance it is possible to amplify the DC tilt angle of 0.2degree at 5V DC bias by a gain factor of over 15X. Next, basic operation by optical modulation was confirmed. The MEMS scanning mirror is connected to the photovoltaic detector and light at 1550nm is projected onto the detector. The 1550nm laser diode output power used to illuminate the detector is directly modulated between 0mW and 7mW by injection current modulation at 350Hz using a function generator in sinusoidal waveform modes. Scanning angle of the MEMS mirror was measured by projecting a red visible diode laser beam at 633nm on the mirror. By tracing the length of line beam created by scanning the mirror the optical scan angle was found to be 8degrees, which is close to the target specification. The scanning angle we achieved is limited by two factors of the present design. Firstly air-damping introduced by the MEMS mirror acts to reduce the amplitude of the scan. Making the mirror smaller can reduce the air-damping effect. The other reason is the limited electrostatic force. The force applied by the comb drive can be improved by increasing the photovoltage generated by the photovoltaic detector and by increasing the size of the comb drive. There is a room for improvement to realize 45 to 90deg angle scanning by optimization of design.

4. CONCLUSION

In this paper a novel endoscope incorporating a low voltage driven MEMS scanner and photovoltaic detector is proposed. Our approach, that utilizes an optically modulated MEMS scanning mirror, eliminates the need for external electrical voltage source. This concept provides an option of the endoscopes scanning operation to be controlled remotely without introducing high voltage signals and wires that can be detrimental to in-vivo diagnosis. We have demonstrated an optical scan angle of 8 degrees utilizing 7mW of 1550nm light modulated at 350Hz to actuate a MEMS mirror. Further improvements and optimization of our design for increasing scan angle, and the development of a compact module will be discussed in future.

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