Electrothermal MEMS fiber scanner for optical endomicroscopy

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Abstract: We report a novel MEMS fiber scanner with an electrothermal silicon microactuator and a directly mounted optical fiber. The microactuator comprises double hot arm and cold arm structures with a linking bridge and an optical fiber is aligned along a silicon fiber groove. The unique feature induces separation of resonant scanning frequencies of a single optical fiber in lateral and vertical directions, which realizes Lissajous scanning during the resonant motion. The footprint dimension of microactuator is 1.28 x 7 x 0.44 mm$^3$. The resonant scanning frequencies of a 20 mm long optical fiber are 239.4 Hz and 218.4 Hz in lateral and vertical directions, respectively. The full scanned area indicates 451 $\mu$m x 558 $\mu$m under a 16 V pp pulse train. This novel laser scanner can provide many opportunities for laser scanning endomicroscopic applications.

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References and links


1. Introduction

Optical endomicroscopy opens up novel clinical techniques such as optical biopsy or image guided surgery [1–3]. Unlike conventional excisional biopsy, optical biopsy can offer non-invasive and on-demand approach to inspect suspected lesions in real time with high resolution and further to minimize a false negative margin during tumor resection. Optical endomicroscope can be mainly achieved by employing assorted laser scanning microscopy such as optical coherence tomography [2,4], confocal [5], photo acoustic [6], or multi-photon [7] microscopy. Recently, microelectromechanical system (MEMS) driven microscanners have accelerated the size reduction of endomicroscopic catheters by using compact, high speed, low operational voltage, and low cost MEMS scanners.

Endomicroscopic catheters are often divided into two different types, i.e., side-viewing and forward-viewing. The side-viewing catheter is achieved by using a rotary motor at the proximal end of the catheter and is well suited for observing vascular organs such as blood vessel or esophagus. Needle probe [8], MEMS mirrors [9,10], or tethered capsule catheter [11] can also serve as a side-viewing catheter. Instead, the forward-viewing catheters are based on MEMS mirrors [4,12], lens scanner [13], or fiber scanners [5,7,14–17], which provide the same viewing direction as conventional endoscopic cameras. In particular, the resonant fiber scanner allows high scanning amplitudes at low operating voltages. A quadratic piezoelectric tube (PZT) has been widely utilized as fiber scanning microactuators due to some technical benefits such as robust packaging, simpleness, and compactness [5,14–18]. Nevertheless, the mechanical coupling between orthogonal directions resulting from manufacturing tolerance still exists as a technical barrier and often results in ellipsoidal patterns during the line scan, which may substantially deteriorate the scan image resolution [19]. More recently, fiber-tethered microstructures effectively reduce the mechanical cross-coupling during two dimensional scanning [15,17,20]. The attached microstructures modulate the effective stiffness of a scanning fiber to separate the resonant scanning frequencies between orthogonal directions and therefore results in Lissajous scanning patterns with high scanning uniformity and low tissue photodamage [16]. However, the PZT fiber scanners still have some technical limitations in further miniaturization and cost reduction.
Here we report an electrothermal MEMS fiber scanner for laser scanning endomicroscopic applications. The MEMS fiber scanner features an electrothermal silicon microactuator with a directly mounted optical fiber (Fig. 1). The silicon microactuator includes double hot arm and cold arm structures with a linking bridge. An optical fiber is aligned along a silicon fiber groove and firmly attached to the linking bridge. During a static electrothermal operation, the optical fiber typically exhibits coupled bi-directional motion, resulting from both the lateral motion (x-direction) due to the difference in thermal expansion between hot and cold arm microstructures and the vertical motion (y-direction) due to that between a hot electrothermal silicon microactuator and a cold optical fiber. This coupled motion can be substantially reduced by scanning an optical fiber at resonance because fiber-attached arm structures differentiate the effective stiffness of a scanning optical fiber and therefore result in the separation of resonant scanning frequencies in both directions. Consequently, a scanning optical fiber exhibits clear line scanned patterns during an electrothermal operation of each resonant frequency and even Lissajous patterns during a concurrent operation of two axis resonant frequencies.

![Fig. 1. Working principle of Lissajous scanned electrothermal MEMS fiber scanner. The MEMS fiber scanner comprises double hot arm and cold arm microstructures with a directly mounted optical fiber. Bi-directional forces are induced by the differences in thermal expansion between double hot arm and cold-arm structures in lateral direction and between microactuator and an optical fiber in vertical direction. The asymmetric structures of microactuator separate resonance frequencies of mounted optical fiber, which allows Lissajous scanning.](image)

2. Device design and fabrication

The electrothermal microactuator enables clear Lissajous scanned patterns from a single optical fiber. Unlike conventional electrothermal microactuators [21–23], the double hot arm structures play an important role for not only determining the electrical resistance but also modulating the effective stiffness of a single optical fiber in orthogonal directions. During electrothermal operation, the displacement of a scanning fiber tip is mainly determined by that of a linking bridge, which increases as the length of double hot arm structures decreases. For instance, a short double hot arm structures has a low electrical resistance, which induces high Joule heating under a constant voltage and therefore results in a large displacement of the linking bridge. The MEMS fiber scanner can be equivalently considered as a mass with two
spring in series, where the effective stiffness of microactuator, an optical fiber, and series-connected system are \( k_A, k_F \), and \( k_{EF} = k_F / (1 + k_F / k_A) \), respectively. The microactuator has different spring constants in both directions; both \( k_Ax \) and \( k_Ay \) are higher than \( k_f \) and particularly, \( k_Ax \) in lateral direction is even higher than \( k_Ay \) in vertical direction. Consequently, the effective stiffness of the system is approximately equal to \( k_f \) in lateral direction and \( k_F / (1 + k_F / k_Ay) \) in vertical direction. It turns out that the resonant scanning frequency in lateral direction is higher than that in vertical direction. In addition, as the arm structure length increases, \( k_Ax \) decreases but \( k_{EFx} \) in lateral direction still remains constant because \( k_Ax \) is much higher than \( k_f \). However, \( k_{EFy} \) in vertical direction substantially decreases because \( k_Ay \) is smaller than \( k_Ax \). It indicates that the resonant scanning frequency in vertical direction, compared to that in lateral direction, apparently decreases as the arm structure length increases. As a result, the separation between resonant frequencies increases with the arm structure length. The effective stiffness and the resonant frequencies of MEMS fiber scanners were precisely calculated by using three dimensional finite element analysis (FEA) with COMSOL multiphysics® ver. 5.1.

![Fig. 2. Electrothermal Lissajous MEMS fiber scanner. (a) Microfabrication procedure. Thin Ti/Au layers firstly deposited on a 6 inch SOI wafer by using thermal evaporation and the electrode pads were wet-etched. Next, top and bottom silicon layers were defined by using DRIE process. A buried oxide layer was then etched in a buffered oxide etchant (BOE). Finally, both the passivation polymers were completely removed by using oxygen plasma. (b) Top-side and (c) Bottom-side SEM images of a fabricated microactuator (Scale bar: 500 μm). (d) An optical image of the microfabricated 6 in. SOI wafer (Scale bar: 50 mm). (e) An optical image of MEMS fiber scanner (Scale bar: 2 mm).](image)

The device fabrication is described in Fig. 2(a). A heavily boron-doped 6 inch silicon-on-insulator (SOI, top 40 μm, bottom 400 μm in thickness, top silicon resistivity: 0.01-0.02 Ω cm) wafer was firstly deposited with thin Titanium / Gold film (Ti: 200 Å, Au: 1000 Å) by using thermal evaporation. The gold electrode pads were photolithographically defined and wet-etched. Both top and bottom silicon layers were defined by using deep reactive ion etching (DRIE). A 2 μm thick buried oxide layer was removed with a buffered oxide etchant (BOE) to release the microactuators and finally both the remaining photoresist layers were completely removed by using oxygen plasma etching. After the device fabrication, individual
microactuators were completely separated from the SOI wafer by using a fused-tether technique with 4 μm wide Y-shape tethers [15,24].

Figures 2(b) and 2(c) show top and bottom SEM images of the electrothermal microactuator, respectively. 80 μm-width hot arm structure was well defined. Gap width between double hot arms was set to be 20 μm. A single mode optical fiber of 125 μm in diameter was mounted in a silicon fiber groove with 160 μm in width. The width of linking bridge was set to be 280 μm to serve as rigid body for a stable vertical motion and the length of a silicon groove was set to be 4 mm in order to avoid the angular misalignment of an optical fiber more than 0.5°. The footprint dimension of an electrothermal microactuator indicates 1.28 x 7 x 0.44 mm3. Figure 2(d) shows an optical image of the fabricated 6 inch SOI wafer, where the microactuators were well defined at a wafer level without a noticeable failure. Figure 2(e) shows an optical image of an electrothermal MEMS fiber scanner, where a 15 mm long single mode fiber (SMF) was permanently mounted along the silicon fiber groove and attached to the linking bridge by precisely microdispensing UV curable epoxy (NOA 63, Norland Products).

3. Device characterization

![Fig. 3. Static and resonant motions of MEMS fiber scanner with a mounted 20 mm long optical fiber. (a) SMF tip displacement depending on an applied voltage (V_{DC}). The displacement of SMF tip increases as applied voltage increases. Both directional displacements are coupled with each other, as shown optical image. (b) Resonance frequency of MEMS fiber scanner. In resonant motion, the scanning fiber has two different modes, i.e., the first mode for vertical motion and the second mode for lateral motion. The cantilever structure of microactuator distinguished the resonance frequencies of the both axis, and the frequency separation increases as the cantilever length increases. (c) Scanning length of the MEMS fiber scanner at resonance. 16 V_{pp} pulse signal (pulse width: 400 μs) is applied to the microactuator. Vertical and lateral scanning length of the fiber decrease as the cantilever length increases.](image-url)
Figure 3 shows the static and resonant motions of electrothermal MEMS fiber scanners. The static and resonant motions were observed with scanning laser beam spots from a 20 mm long SMF tip. In static motion, both directional displacements of a SMF tip increase with an applied voltage from 0 V DC to 18 V DC and they are clearly coupled during the static electrothermal operation (Fig. 3(a)). In resonant motion, the scanning fiber has two different modes, i.e., the first mode for vertical motion and the second mode for lateral motion (Fig. 3(b)). As mentioned earlier, the resonant scanning frequency in vertical direction decreases as the length of arm structures increases whereas that in lateral direction still remains relatively constant because the effective stiffness of microactuator in vertical motion substantially reduces as the arm structure length increases, compared to that in lateral motion. Consequently, the frequency separation increases with the length of arm structures and the experimental results well match with the FEA results. The frequency separation over the full bandwidth enables the substantial reduction of mechanical cross-coupling between two orthogonal directions. Besides, the scanning length of MEMS fiber scanner clearly depends on the arm structure length (Fig. 3(c)). The MEMS fiber scanners with different arm structures in length were operated at the corresponding resonant frequencies for both directions under a rectangular 16 V pp pulse train (pulse width = 400 μs, duty rate = 0.13 and power consumption = 90mW), respectively. Note that this rectangular pulse train allows the maximum scanning length owing to a sufficient cooling time during electrothermal operation. The experimental result also demonstrates that the scanning lengths in both directions decrease as the arm structure length increases due to large electrical resistance under a constant voltage operation. The trade-off between frequency separation and the scanning length can be overcome by using additional silicon structure [15, 17].

![Fig. 4. Lissajous scanning of the MEMS fiber scanner. (a) Frequency response of the scanner. Two resonance peaks are clearly decoupled. (b) A pulse train for Lissajous scanning. Two different pulses with resonant frequencies in both directions are mixed, which is a squared root of square of lateral pulse train and vertical pulse train, respectively. Next, overlapped pulse trains are reduced for stable operation. (c) and (d) Optical images of laser scanning patterns in lateral and vertical directions, respectively. (e)-(f) Time elapsed Lissajous scanning patterns (1/50 sec, 1/8 sec) at 16 V pp pulse train (Scale bar: 300 μm).]
Figure 4 demonstrates two dimensional laser scanning patterns by using the MEMS fiber scanner. Figure 4(a) shows scanning frequency responses of the MEMS fiber scanner. A 20 mm long fiber mounted on the MEMS fiber scanner resonantly scans at 239.4 Hz for lateral direction and 218.4 Hz for vertical direction and thus clearly exhibits the complete frequency separation over the full bandwidth at each resonance. The mechanical Q-factor is 77 for lateral motion and 145 for vertical motion, which allows large field-of-view (FOV) scanning at low operating voltages. Lined scanning patterns are shown clearly in Fig. 4(c) and (d). The scanning patterns were clearly captured at the tip end of a single mode fiber by using a CMOS camera. Furthermore, Lissajous scanning was successfully achieved by applying the modulated pulse train, i.e., a square root of the sum of squared rectangular pulses at two different resonant frequencies of lateral and vertical directions (Fig. 4(b)). The voltage amplitudes over 16 Vpp at the common multiples of pulse trains at two different resonant frequencies were additionally cut-off for stable scanning. Finally, Fig. 4(e) and 4(f) show Lissajous scanning patterns with a field-of-view (FOV) of 451 μm x 558 μm at 16 Vpp pulse train (pulse width: 500 μs), where the fill-factor of scanning patterns continuously increases as the scanning time increases.

4. Conclusion

To conclude, we have demonstrated electrothermal Lissajous MEMS fiber scanners for optical endomicroscopic applications. Two dimensional laser scanning was successfully achieved by using bi-directional actuation of the MEMS fiber scanner. The unique feature of microactuators induces the separation of resonant scanning frequencies of a single optical fiber in lateral and vertical directions, which realizes Lissajous scanning without additional actuators or structures. The footprint dimension of microactuator is 1.28 x 7 x 0.44 mm³ and the operating frequencies of lateral and vertical direction are 239.4 Hz and 218.4 Hz with a 20 mm long optical fiber. The assembled MEMS fiber scanner shows lateral, vertical, and Lissajous scanning patterns at resonance. The full scanned area indicates 451 μm x 558 μm under a 16 Vpp pulse train operation. This MEMS fiber scanner gives ultrathin dimensions as well as low cost, compared to conventional piezotube (PZT) fiber scanners. This novel endomicroscopic scanner provides many opportunities for laser scanning endomicroscopic applications based on OCT, confocal, or multi-photon microscopy.

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