Published in final edited form as:

Sens Actuators A Phys. 2014 August 15; 215: 89–95. doi:10.1016/j.sna.2013.09.035.

MEMS-BASED 3D CONFOCAL SCANNING MICROENDOSCOPE USING MEMS SCANNERS FOR BOTH LATERAL AND AXIAL SCAN

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Abstract

A fiber-optic 3D confocal scanning microendoscope employing MEMS scanners for both lateral and axial scan was designed and constructed. The MEMS 3D scan engine achieved a lateral scan range of over $\pm 26^\circ$ with a 2D MEMS scanning micromirror and a depth scan of over 400 μm with a 1D MEMS tunable microlens. The lateral resolution and axial resolution of this system were experimentally measured as 1.0 μm and 7.0 μm , respectively. 2D and 3D confocal reflectance images of micro-patterns, micro-particles, onion skins and acute rat brain tissue were obtained by this MEMS-based 3D confocal scanning microendoscope.

Keywords

3D confocal imaging; 3D microendoscope; MEMS mirror; MEMS tunable lens; electrothermal actuator; bimorph; large scan range

1. Introduction

Confocal scanning microscopy has gained extensive applications in biomedical imaging, industrial inspection and metrology for its superior resolution, high contrast and powerful optical sectioning capacity [1-3]. It has revolutionized optical microscopy by introducing point-by-point illumination and pinhole filtering. However conventional confocal scanning microscopes are bulky and only suitable for lab use. Recently confocal scanning microendoscopy has emerged as a new imaging technology that extends the superior capability of confocal scanning microscopy to *in vivo* imaging of internal organs such as GI tracts, liver, and pancreatic duct, etc [4]. It promises to enable *in vivo* optical biopsy and noninvasive cancer detection. The challenges for 3D confocal scanning microendoscopy,

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however, include the miniaturization of laser beam scan engines especially for both lateral and axial scans, the requirement of large scan range under low drive voltage, and the miniaturization of the optics without largely sacrificing optical performance.

In confocal scanning microendoscopy, the image pixel scanning can be obtained by scanning the laser beam across a fiber bundle at the proximal end [5-8]. Using a fiber bundle avoids the scan at the distal end, thereby simplifying the miniaturization of the image probe. The limitations of fiber bundle scanning are the inherent pixilation artifact of the fiber bundle because of the spacing between fibers, the cross talk and reduced contrast [1, 9].

More promisingly, many researchers demonstrated laser beam scanning at the distal end by utilizing MEMS mirrors [10-15]. MEMS scanners can provide continuous beam scan with high stability, uniform coupling and multidimensional scan capability at small footprint. For example, a 2D confocal microscope employing a 2D electrostatic micromirror for lateral scan was reported by H. J. Shin *et al.* [10], but depth scan was absent in this system. A 2D confocal microscope previously reported by the authors in [11] was able to perform depth scan by a large-tunable-range MEMS lens-scanner, but lateral scan was accomplished by a bulky motorized stage which limited its application in endoscopic imaging. 3D confocal microscopes using MEMS mirrors for lateral scan were presented by C.L. Arrasmith *et al.* [12] and W. Piyawattanametha *et al.* [13], but both of the reported systems relied on external motors and sliding stages for depth scan, which suffered from instability from frictions as well as size and speed limitations. An on-chip 3D confocal microscope was reported by C. Gorecki *et al.* [14], in which two electrostatic scanning microlenses were stacked with the 1D z-axis scanning microlens generating a 100 μm depth scan at 50 V and the x-y scanning microlens producing a 30 μm lateral scan at 200 V. The required high voltages may pose safety concerns if applied inside human body. A 3D confocal microscope using an electrostatic micromirror for lateral scan and another electrostatic micromirror for depth scan was reported by J. Jeong *et al.* [15], but it had small static axial displacement (10 μm) at high voltage (200 V) and the displacement was still limited ($\pm 27.5 \mu\text{m}$) even at resonance.

In this paper, a confocal scanning microendoscope is presented, which incorporates a miniature MEMS 3D scan engine that can generate both large axial and lateral scan ranges under low drive voltage. The lateral scan is performed by a 2D scan micromirror and the depth scan by a focal-tunable microlens. These two MEMS scanners together with high-quality micro-optics are packaged into a compact fiber-optic endoscopic probe. Polarization is also used to minimize the back-reflection and increase signal to noise ratio.

This paper is arranged as follows. The confocal scanning microendoscope system including system design, endoscopic probe design and optical simulations is described in Section 2. Then in Section 3, the device design, fabrication process and characterization of the MEMS scanners are presented. After that, the imaging experimental results including system characterizations and 2D and 3D confocal reflectance images are reported in Section 4.

2. MEMS-based 3D Confocal Laser Scanning Microendoscope

The schematic of the fiber-optic confocal microendoscope system is shown in Fig. 1. The system incorporates polarization-sensitive components to suppress unwanted back-

reflections. The laser beam (center wavelength: 638 nm) from the laser diode (CLAS2-638-100C, Blue Sky Research) first propagates through a spatial filter (M-900, Newport), which uses a pinhole to filter out the high spatial frequencies and produces a clean Gaussian beam to launch into the system. After that, the laser beam is then collimated to 1 mm in diameter by a lens. A polarizing beam splitter (PBS) then reflects the s-polarized light at 90° while transmitting the p-polarized light. The reflected s-polarized light is coupled into a single-mode polarization maintaining (PM) fiber (P1-630PM, Thorlabs) by a fiber coupler (PAF-X-5, Thorlabs). The PM fiber maintains the light polarization direction along the fiber cord and then delivers the linearly-polarized light into the endoscopic probe.

The endoscopic probe as shown in Fig. 2 comprises a GRIN lens, a quarter wave plate (QWP), a MEMS 2D scan mirror, a fixed mirror, a pair of achromatic lenses and a MEMS tunable objective lens. The quarter-pitch GRIN lens collimates the diverging light exiting from the fiber core. The diameter of the GRIN lens is 2 mm and the length is 5.17 mm. The linearly-polarized beam, after passing through the GRIN lens, is incident on the QWP at 45° to the optic axis of the QWP. The linearly s-polarized light is divided into two equal orthogonal electric field components with one component retarded by a quarter of the wavelength by the QWP, therefore producing a circularly-polarized light output. Then a MEMS 2D scan mirror perform the two-dimensional lateral scan of the collimated light beam, followed by a fixed mirror tilted at 45° to fold the light path by 90°. A pair of achromatic lenses (Edmund Optics) is then employed for beam expansion as well as aberration correction. After that, a 1D MEMS tunable objective lens is used to focus the beam and also perform the depth scan.

The backreflected/backscattered light from the sample propagates back through the probe and passes consequentially through the MEMS tunable objective lens, the beam expander lens pair, the fixed mirror and the MEMS 2D mirror. Then the light passes through the QWP for the second time with another quarter wavelength retardation introduced by the QWP, which changes the circularly-polarized light to linearly p-polarized light. The p-polarized signal light is then focused by the GRIN lens, coupled back into the PM fiber, transmitted by the PBS, detected by an avalanche photodetector (APD) (C54601-01 Hamamatsu), and collected by a DAQ to a PC. Meantime, the unwanted specular reflections at the fiber end and the GRIN lens end-face remain s-polarized and thereby are reflected by the PBS without entering the detector.

The optical path of the endoscopic probe in Fig. 2 is given in Fig. 3(a). The single-mode PM fiber has a NA of 0.14. The GRIN lens has a quarter pitch. The beam at the end of the GRIN lens is 0.54 mm in diameter, which will under-fill the objective and lead to small effective NA. So a pair of beam expander lenses (Edmund Optics, $f_1 = 6$ mm, $f_2 = 20$ mm) is used to expand the beam by $3.33 \times$ to 1.8 mm in diameter. These two lenses form a telecentric system with a beam expansion factor of 3.33. The beam-expander pair is also used for aberration correction. The objective is an aspheric lens with $f = 1.45$ mm and $NA = 0.55$. The collimated light beam after the beam-expander overfills the aperture of the aspheric objective; therefore the NA of the system is equal to the NA of the aspheric objective. The objective is scanned in axial direction by the MEMS lens scanner to perform depth scan. The MEMS mirror is located at the conjugate plane of the back focal plane of the objective.

Fig. 3(b) shows the spot diagram calculated by ray tracing in CODE V. The RMS spot sizes at optical scan angles of 0° , 6° , and 12° are $0.49\text{ }\mu\text{m}$, $0.88\text{ }\mu\text{m}$, and $2.8\text{ }\mu\text{m}$, respectively. Scanning the MEMS mirror at larger angle will introduce larger aberration and lead to lower resolution.

3. MEMS scanners

3.1 MEMS tunable lens for depth scan

An electrothermal tunable microlens is used to perform the depth scan in the confocal scanning microendoscope. The tunable MEMS lens consists of a MEMS lens-scanner with a central opening (Fig.4(a)) and a 2.4 mm-diameter glass objective lens assembled onto the platform of the scanner (Fig.4(b)). The central platform in the MEMS lens-scanner is symmetrically supported by four electrothermal lateral-shift-free large-vertical-displacement (LSF-LVD) actuators [16] at two sides (Fig.4 (a)). The LSF-LVD actuator is composed of three Al/SiO₂ bimorphs with two rigid frames connected in between. The actuation mechanism is electrothermal actuation, with a thin layer of Pt embedded along the bimorphs as the heater. The large initial elevation due to residual stresses in the bimorph beams provides space for the platform to displace vertically in large range. Good stability and robustness are achieved by using wide actuator beams and connecting a large array of parallel actuator beams to each side of the platform. The platform is elevated upward at about $800\text{ }\mu\text{m}$ after the device release due to the residual stresses in the bimorph beams.

The platform, together with the objective lens, will be actuated downward when an electrical current passes through the Pt heater in the bimorph beams, which introduces Joule heating and thereby bending of the bimorph beams. A miniature glass lens with a diameter of 2.4 mm, a NA of 0.55 and a back focal length of 0.88 mm is selected as the objective lens for this system. The lens is fixed by UV glue to the platform with the clear aperture of the lens aligned to the central opening of the platform. The vertical elevation of the platform after the lens being assembled is $510\text{ }\mu\text{m}$. The device footprint of the lens scanner is $4.4\text{ mm} \times 4.4\text{ mm}$.

The MEMS lens scanner was fabricated on a SOI substrate with a $40\text{ }\mu\text{m}$ -thick device layer by a combined surface-and bulk-micromachining process. As outlined in Fig. 5, the process starts with a PECVD deposition of $1.1\text{ }\mu\text{m}$ -thick SiO₂ on the SOI wafer (a). This SiO₂ layer serves as the bottom layer of bimorphs. Then a Cr/Pt/Cr film of $20\text{nm}/0.2\text{ }\mu\text{m}/20\text{nm}$ is sputtered, and patterned by lift-off process on top of the $1.1\text{ }\mu\text{m}$ -thick SiO₂ layer (b). After that, a $0.15\text{ }\mu\text{m}$ -thick PECVD SiO₂ layer is deposited and patterned with RIE dry etch for electrical isolation (c). Next, a $1\text{ }\mu\text{m}$ -thick Aluminum layer is evaporated and lifted-off to form the top structure layer of the bimorphs and the mirror plate surface as well (d). A second PECVD SiO₂ layer is then deposited and dry etched to form a hard mask for the front-side silicon etch (e). Then, a back-side bulk silicon etch is performed until the etch stops at the buried oxide, followed by RIE etch of the buried oxide (f). Finally, an anisotropic silicon etch is performed to etch through the device layer (g), followed by an isotropic silicon etch to undercut and release the bimorphs (h).

The vertical displacement and frequency response of this device were experimentally measured and shown in Fig. 6(a) and Fig. 6(b) [17]. The vertical displacement was measured by an Olympus BX51 microscope equipped with a QC200 micro-position recorder. To measure the vertical displacement, the lens scanner was operated at the piston mode by simultaneously driving all the actuators with a same dc voltage. After each step of the dc voltage change, the microscope was refocused onto the mirror plate and the coordinates of multiple points on the mirror plate were recorded. A vertical actuation range of 400 μm was obtained at only 2 V (Fig. 6(a)). The frequency response was measured using a Polytec OFV-511 laser Doppler vibrometer. The frequency response of the assembled lens scanner is shown in Fig. 6(b) with the first resonance peak at about 24 Hz.

3.2 MEMS scanning mirror for 2D lateral scan

3.2.1 Device design—The 2D lateral scan in the confocal scanning microendoscope is performed by an electrothermal MEMS mirror with a footprint of 2 mm $\times$ 2 mm (Fig. 7). A 1 mm $\times$ 1 mm mirror plate is supported by four identical and symmetrically located inverted-series-connection (ISC) bimorph actuators at the four sides of the mirror plate [18]. Each ISC bimorph actuator consists of inverted bimorphs, non-inverted bimorphs, and sandwiched overlaps connected in series to form an double S-shaped beam. Fig. 7(a) and Fig. 7(b) show an SEM picture of one ISC actuator and an SEM of the MEMS mirror, respectively. This mirror was fabricated using the same process shown in Fig. 5.

3.2.2 Device characterization—Tip-tilt motion was generated by differentially driving two opposite actuators of the mirror. The mirror scans optical angles of $\pm 26^\circ$ at 4.5V as shown in Fig. 8(a). The frequency response was measured also using a Polytec OFV-511 laser Doppler vibrometer. The frequency response of the mirror is given in Fig. 8(b) showing the resonance at 460 Hz.

4. System integration and imaging experiments

4.1 System integration

As shown in Fig. 9, the assembled probe has a diameter of 7 mm. The probe mount consists of three separate precision-machined metal pieces. The first piece is designed to hold the fiber, GRIN and QWP. The fiber with the end cleaved is inserted into the trench machined in the first metal piece. The GRIN lens is then placed next to the fiber end with its end face adhesively attached to the fiber tip by optical UV glue. After that, the QWP is inserted and carefully rotated to align its optical axis at 45° to the incident light polarization direction. The second metal piece is used to house the MEMS mirror, fixed mirror and the first expander lens, while the third piece is loaded with the second expander lens and the MEMS tunable objective. Flexible printed circuit boards (FPCBs) are used for electrical connections. Two FPCBs are first glued on the metal pieces and then the MEMS mirror and MEMS lens are placed and glued on top of the FPCBs. Then silver epoxy is used to electrically connect the MEMS devices to the FPCBs. Finally, the three metal pieces are adhesively assembled together to form a complete endoscopic probe. The diameter of the endoscopic probe is in the larger side for endoscopic applications and it may be reduced by minimizing the MEMS devices and improving the optical design so high optical

performance can be achieved at smaller sizes of the optics. The endoscopic probe is integrated with the polarization-sensitive confocal scanning microendoscope system.

4.2 System characterization

Both lateral and axial resolutions of the confocal microendoscopy system have been characterized. Fig. 10(a) shows an *en face* confocal reflectance image of the elements in Group 7 of a USAF resolution target by the confocal imaging system. There is some distortion in the image because the fast axis of the MEMS mirror scans arc patterns near the resonance peak and the scan speed of the mirror is not exactly uniform along the scan path. The distortion can be corrected by mapping the 2D scan paths of the mirror under the same voltage and frequency settings and then transforming the image data by a correction matrix. The resolution would degrade as the beam scans towards the edge of the field of view, but the reflectance image of the resolution target shows that the smallest pattern with a width of $2.2\ \mu\text{m}$ is still resolvable. In order to find out the actual lateral resolution, the reflective chrome surface of the USAF resolution target was laterally translated on the focal plane and the 10%--90% edge width was measured as $1.0\ \mu\text{m}$, as shown in Fig. 10(c). The axial resolution was measured by translating a mirror surface axially across the focal plane and recording the change of the signal strength detected by the APD; the FWHM axial resolution was found to be $7.0\ \mu\text{m}$, as shown in Fig. 10(b). The lateral and axial resolution can be further improved by increasing the numerical aperture of the objective lens, reducing the aberrations, or adding a lens immersion medium.

4.3 Confocal imaging results

Confocal imaging experiments have been performed using this MEMS-based confocal scanning microendoscope system. 2D and 3D confocal reflectance images of micro-patterns (Fig. 11), micro-particles embedded in PDMS (Fig. 12) and Onion skin (Fig. 13) have been obtained.

During the experiments, the four actuators of the 2D MEMS mirror were grouped into two pairs with each pair including two actuators at the opposite sides of the mirror plate. The actuator pair controlling the x-scan was differentially driven with a ramp waveform of $0 \sim 2\ \text{V}$ at $450\ \text{Hz}$. The scan in x- direction is driven near the resonance peak for large scan angle. The actuator pair driving the y- direction scan was differentially driven with a ramp waveform of $0 \sim 4\ \text{V}$ at $0.75\ \text{Hz}$. The 2D *en face* images have 300×300 pixels. Meanwhile, the z-direction scan was performed by simultaneously driving all the actuators of the MEMS lens scanner with a ramp waveform of $0 \sim 2\ \text{V}$ at $1\ \text{mHz}$.

Fig. 11 (a) shows a 2D reflectance confocal image of micro-patterns on the USAF resolution target. The micro-patterns shown in the figure include a number and a bar. Fig. 11(b) is a 3D volume-rendered image of the USAF resolution target covered by a $200\text{-}\mu\text{m}$ thick glass cover slide. The layers from up to down are the top surface of the glass slide, the bottom surface of the glass slide, and the micro-patterns. The imaging volume shown in this figure is $180\ \mu\text{m} \times 180\ \mu\text{m} \times 400\ \mu\text{m}$.

Fig. 12(a) shows a stack of 2D reflectance confocal images of the micro-particles acquired at different depths of the sample. The micro-particles are alloy particles with the diameters in the range of a few microns to tens of microns. The driving voltages on the MEMS lens scanner from the top slice to the bottom slice were 1.6 V, 1.3 V and 1.0 V, corresponding to the axial displacements of 281 μm , 197 μm and 133 μm , respectively. Fig. 12(b) is a 3D image of the micro-particles reconstructed by stacking the 2D image slices. The image volume shown in this figure is 180 $\mu\text{m} \times 180 \mu\text{m} \times 250 \mu\text{m}$.

Fig. 13(a) and Fig. 13(b) are the 2D and 3D confocal reflectance images of onion skin sample. The imaging volume shown in this figure is 180 $\mu\text{m} \times 180 \mu\text{m} \times 270 \mu\text{m}$. Fig. 14 (a) and Fig. 14(b) are the 2D and 3D confocal reflectance images of an acute rat brain tissue sample. The imaging volume shown in this figure is 180 $\mu\text{m} \times 180 \mu\text{m} \times 380 \mu\text{m}$.

5. Summary

In conclusion, we have developed a confocal scanning microendoscope using MEMS devices for both lateral and axial scans. The full-MEMS 3D scan engine has been demonstrated as a viable way to achieve large-scan-range 3D confocal imaging at low voltage and small size. 2D and 3D confocal reflectance images of micro-patterns, micro-particles embedded in PDMS, onion skin and rat brain tissue have been obtained by this system. The axial and lateral resolutions are 7.0 μm and 1.0 μm , respectively. Due to its small size and 3D imaging capability, this miniature MEMS-based confocal microendoscope may be used for early cancer diagnosis.

Acknowledgments

This work was funded in part by the National Science Foundation under award#1002209 and the National Institutes of Health R01 CA153023. The MEMS devices were fabricated at the Nanoscale Research Facility at the University of Florida.

Biography

Lin Liu received her B.S. degree in optoelectronics from the Huazhong University of Science and Technology, Wuhan, Hubei, China in 2008. She is currently working towards a Ph.D. degree in electrical and computer engineering from the University of Florida. Her graduate research involves the design and fabrication of MEMS devices including micromirrors, microlenses and fiber scanners, and their applications in endoscopic imaging including endoscopic confocal imaging, optical coherence tomography and nonlinear optical imaging.

Erkang Wang is a graduate student in electrical engineering at the University of Florida, USA and will receive his master degree in May, 2013. He has been working in the Interdisciplinary Microsystems Group in the University of Florida as a research assistant specialized in MEMS based confocal microscopy under the supervision of Prof. Huikai Xie.

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Huikai Xie received his MS and Ph.D. degrees in electrical and computer engineering from Tufts University in 1998 and Carnegie Mellon University in 2002, respectively. He joined the University of Florida in 2002, where he is currently a professor at Department of Electrical and Computer Engineering. His research interests include MEMS/NEMS, integrated sensors, microactuators, integrated power passives, CNT-CMOS integration, optical MEMS, IR sensors, biophotonics, and biomedical imaging. He has published over 200 technical papers, and holds more than 30 patents. He is a senior member of IEEE and OSA and a member of SPIE.

References

1. Pawley, JB. Handbook of Biological Confocal Microscopy. Springer; 2006.
2. Sheppard C, Wilson T. Depth of field in the scanning microscope. Opt. Lett. 1978; 3:115–117. [PubMed: 19684715]
3. Gu M, Sheppard C, Gan X. Image formation in a fiber-optical confocal scanning microscope. JOSA A. 1991; 8:1755–1761.
4. Neumann H, Kiesslich R, Wallace MB, Neurath MF. Confocal laser endomicroscopy: technical advances and clinical applications. Gastroenterology. 2010; 139:388–392. e2. [PubMed: 20561523]
5. Gmitro AF, Aziz D. Confocal microscopy through a fiber-optic imaging bundle. Opt. Lett. 1993; 18:565–567. [PubMed: 19802201]
6. Carlson K, Chidley M, Sung K, Descour M, Gillenwater A, Follen M, Richards-Kortum R. In vivo fiber-optic confocal reflectance microscope with an injection-molded plastic miniature objective lens. Appl. Opt. 2005; 44:1792–1797. [PubMed: 15813514]
7. Rouse AR, Kano A, Udovich JA, Kroto SM, Gmitro AF. Design and demonstration of a miniature catheter for a confocal microendoscope. Appl. Opt. 2004; 43:5763–5771. [PubMed: 15540433]
8. Knittel J, Schnieder L, Buess G, Messerschmidt B, Possner T. Endoscope-compatible confocal microscope using a gradient index-lens system. Opt. Commun. 2001; 188:267–273.
9. Komiyama A, Hashimoto M. A new class of crosstalk in image fibers. Opt. Commun. 1994; 107:49–53.

10. Shin H, Pierce MC, Lee D, Ra H, Solgaard O, Richards-Kortum R. Fiber-optic confocal microscope using a MEMS scanner and miniature objective lens. *Opt. Express*. 2007; 15:9113–9122. [PubMed: 19547251]
11. Liu L, Wu L, Zory P, Xie H. Fiber-optic confocal microscope with an electrothermally-actuated, large-tunable-range microlens scanner for depth scanning, *Micro Electro Mechanical Systems (MEMS)*. 2010 IEEE 23rd International Conference on. 2010:827–830.
12. Arrasmith CL, Dickensheets DL, Mahadevan-Jansen A. MEMS-based handheld confocal microscope for in-vivo skin imaging. *Optics express*. 2010; 18:3805–3819. [PubMed: 20389391]
13. Piyawattanametha W, Wang TD. MEMS-based dual-axes confocal microendoscopy, *Selected Topics in Quantum Electronics. IEEE Journal of*. 2010; 16:804–814.
14. Gorecki C, Nieradko L, Bargiel S, Dziuban J, Henis D, Sylvestre J, Alkowska K, Soto-Romero G, Thevenet J, Yahiaoui R. On-chip scanning confocal microscope with 3D MEMS scanner and VCSEL feedback detection, *Solid-State Sensors, Actuators and Microsystems Conference, 2007. TRANSDUCERS 2007. International Conference on*. 2007:2561–2564.
15. Jeong J, Mandella MJ, Kino GS, Contag CH, Solgaard O. 3-D MEMS scanning system for dual-axis confocal microendoscopy, *Optical MEMS and Nanophotonics (OMN)*. 2011 International Conference on. 2011:71–72.
16. Wu L, Xie H. A large vertical displacement electrothermal bimorph microactuator with very small lateral shift. *Sensors and Actuators A: Physical*. 2008; 145:371–379.
17. Liu L, Wang E, Zhang X, Tang Y, Xie H. Confocal microendoscopic 3D imaging using MEMS scanners for both lateral and axial scans, *Micro Electro Mechanical Systems (MEMS)*. 2013 IEEE 26th International Conference on. 2013:1085–1088.
18. Jia K, Pal S, Xie H. An electrothermal tip-tilt-piston micromirror based on folded dual S-shaped bimorphs, *Microelectromechanical Systems. Journal of*. 2009; 18:1004–1015.

Highlights

1. A new MEMS-based 3D confocal scanning microendoscope has been designed, constructed and experimentally verified.
2. The compact fiber-optic endoscopic probe integrates the MEMS scanners, fiber and high-quality micro-optics.
3. Both lateral scan and axial scan are performed by MEMS devices with large scan ranges and low drive voltages.
4. Polarization sensitive components have been employed to suppress unwanted reflections.
5. 2D and 3D confocal reflectance images of various samples have been obtained with high resolutions.

Fig. 1.
Systematic design of 3D confocal scanning microendoscope.

Fig. 2.
3D model of the endoscopic probe design.

Fig. 3.

(a) Optical design of the endoscopic probe. (b) Spot diagram at different field angles: RMS spot size= $0.49\text{ }\mu\text{m}$ at 0° ; RMS spot size= $0.88\text{ }\mu\text{m}$ at 6° ; RMS spot size= $2.8\text{ }\mu\text{m}$ at 12° .

Fig.4.
(a) SEM of a lens-scanner. (b) Photograph of an assembled tunable lens.

Fig.5.
Fabrication process of the MEMS lens scanner

Fig.6.
 (a) Z displacement vs. voltage of the MEMS tunable lens. (b) Frequency response of the MEMS tunable lens.

Fig.7.
(a) SEM of an ISC actuator. (b) SEM of the 2D MEMS mirror.

Fig.8.

(a) Optical scan angle vs. driving voltage of the MEMS mirror. (b) Frequency response of the MEMS mirror.

Fig. 9.
Photograph of the assembled the endoscopic probe.

Fig.10.

(a) Reflectance image of group 7 elements in a USAF resolution target. The smallest elements are $2.2\ \mu\text{m}$ wide. (b) Axial resolution measurement. (c) Lateral resolution measurement.

Fig. 11.

3D volume-rendered image of micro-patterns under a 200-μm thick glass slide. The layers from up to down are the top surface of the glass slide, the bottom surface of the glass slide, and the micro-patterns.

Fig.12.

(a): stack of 2D confocal reflectance images of the micro-particles at different depths. The driving voltages of the MEMS lens scanner from up to bottom are at: 1.6 V, 1.3 V, and 1 V. The image sizes are $180\ \mu\text{m} \times 180\ \mu\text{m}$. (b) 3D volume-rendered image of the micro-particles embedded in PDMS.

(a)

(b)

Fig. 13.

(a): 2D confocal reflectance image of onion skin. (b) 3D volume-rendered image of onion skin.

Fig. 14.
(a): 2D confocal reflectance image of acute rat brain tissue. (b) 3D volume-rendered image of rat brain tissue.