Integration of a Double-clad Photonic Crystal Fiber, a GRIN Lens and a MEMS Mirror for Nonlinear Optical Endoscopy

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Abstract: We report on a prototype of a nonlinear optical endoscope based on a double-clad photonic crystal fiber and a GRIN lens to improve the detection efficiency and a MEMS mirror to steer the beam.

1. Introduction

Nonlinear optical microscopy by using nonlinear optical effects such as two-photon absorption and second harmonic generation (SHG) exhibits advantages of an inherent sectioning ability, relatively deep optical penetration, and direct visualization of intrinsic indicators within biological tissue [1,2]. To achieve compact and miniature nonlinear microscopes for *in vivo* applications, micro optics or flexible fiber-optic components such as optical fibers and optical fiber couplers are usually integrated into the imaging system to replace complicated bulk optics [3-6]. Although single-mode fibers (SMFs) can deliver a high quality laser beam and provide an enhanced sectioning capability due to the effective pinhole effect compared with multimode fibers or fiber bundles, the lower numerical aperture (NA) and the finite core size of the SMF give rise to a restricted sensitivity of a nonlinear optical microscope system. The utilization of photonic crystal fibers (PCFs) has led many innovative fiber-optic imaging devices [7-9]. Recently, a nonlinear optical microscope based on the use of a single length of the double-clad PCF has been constructed [10]. Our results have demonstrated that the signal collection efficiency in a nonlinear optical microscope based on a double-clad PCF is approximately two orders of magnitude higher than that in a microscope based on a standard SMF [10]. However, in order to perform *in vivo* nonlinear optical imaging in the internal organs, the development of an endoscope probe is essential to deliver, steer and collect optical beam. In this paper, we report a miniaturized nonlinear optical microscope based on a double-clad PCF and a MEMS scanning mirror. The endoscope-based line profiles from rat tail tendon and esophagus have been successfully obtained, which demonstrates the promising potential for developing a real-time nonlinear optical endoscope to enable early cancer detection at the cellular level.

2. Endoscope Design

An ultra-small probe head is designed to fit the working channel of a flexible endoscope and connect to the bulk optical components via a flexible fiber, as shown in Fig. 1(a). The excitation laser beam coupled from the double-clad photonic crystal fiber [10] is reflected and scanned one-dimensionally by a MEMS mirror with a maximum rotation angle of 17 degrees [11]. A GRIN lens is used to focus the scanned laser beam at its back surface onto a sample. The double-clad PCF we used (Fig. 1(b)) can play a dual role to offer the robust single-mode guidance of near-infrared light in the central core and the efficient propagation of visible light within the multimode inner cladding [10]. The MEMS mirror shown in Fig.1 (c) is 1 mm by 1mm in size, coated with aluminium. It has a resonance frequency of 165 Hz, exceeding the scanning speed and angle requirements for most endoscopic applications [11]. As a consequence, the endoscope head of the prototype system is approximately 3 mm in diameter, equipped with the MEMS mirror and the GRIN lens.

3. Endoscopic imaging using a MEMS mirror

Rat tail tendon is used to characterize the nonlinear optical endoscope which is comprised of the double-clad PCF, the GRIN lens, and the MEMS mirror. Rat tail tendon consists of abundance of Type I collagen fibrils, which can be modelled in wound healing, malignancy, and development. Fig. 2(a) illustrates a series of SHG line profiles from rat tail tendon with a depth spacing of 10 μm. In this case, a 0.2-pitch GRIN lens

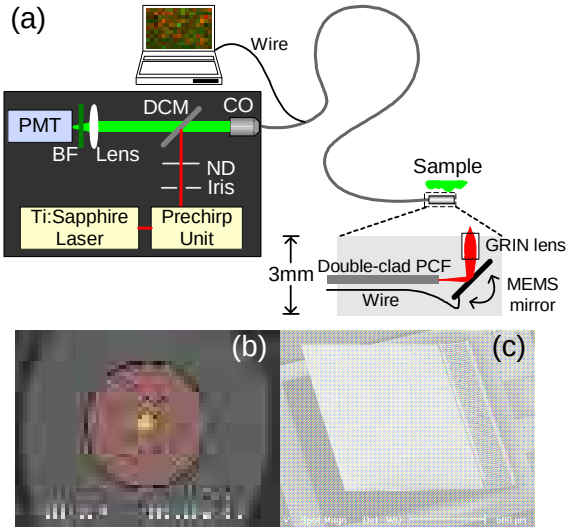

Fig.1 (a) Schematic diagram of the nonlinear optical endoscope. The endoscope probe is based on a double-clad PCF, a MEMS mirror, and a GRIN lens. (b) A far-field output pattern from a double-clad PCF at wavelength 800 nm overlaid on a SEM image. (c) A SEM image of the MEMS mirror.

having a diameter of 1 mm is used and the field of view on the sample is approximately 35 μm which corresponds to an optical scanning angle of approximately 6 degrees of the MEMS mirror. Only 5 V is needed to obtain 6-degree rotation. In our experiments, as the laser beam is scanned at the back surface of the GRIN lens, the GRIN lens is underfilled and results in an axial resolution of approximately 10 μm. Further, a SHG line profile from the rat esophagus tissue is shown in Fig. 2(b). The rat esophagus was removed from a euthanized rat, immersed in Hank's balanced salt solution (no phenol red) and imaged directly without any staining. The excitation power on the sample resulting in SHG signals is approximately 30 mW. To our best knowledge, our result is the first report on nonlinear optical imaging of unstained rat esophagus tissue with a miniaturized nonlinear optical microscope based on a single fiber and a MEMS mirror.

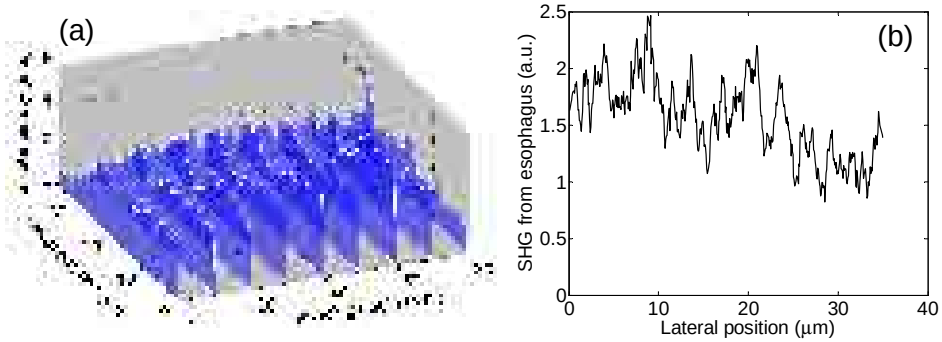

Fig. 2 (a) A series of SHG line profiles taken at a 10-μm step into rat tail tendon. (b) A SHG line profile from unstained rat esophagus tissue.

4. Conclusion

We have demonstrated experimentally the concept of nonlinear optical endoscopy based on a double-clad PCF, a GRIN lens and a MEMS mirror. A double-clad PCF has been used to deliver the pulsed excitation beam and collect nonlinear optical signals with a detection efficiency enhanced by 160 times. Using a MEMS mirror as the scanning unit and a GRIN lens to produce a fast scanning focal spot offers a great potential to develop a compact endoscope probe for *in vivo* applications.

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