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Stationary-fiber rotary probe with unobstructed 360° view for optical coherence tomography

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A side-scanning fiber probe is a critical component for optical coherence tomography in medical imaging and diagnosis. We propose and fabricate an on-axis rotating probe that performs *in situ*, circumferential scanning that is shadow-free (not susceptible to shadow effects caused by the motor's wires). A miniature motor that incorporates a bored-out shaft for the optical fiber is located at the distal end of the probe, which results in a more stable and uniform circumferential scan, free from wire-shadow interference effects. More importantly, this design, novel to our knowledge, compared to other probes avoids the insertion losses introduced by optical coupling components and the multitude of optical interfaces, which is very important for sensing weak signals backscattered from structures deep in the tissue. © 2011 Optical Society of America

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One of the advantages of the fiber-based optical coherence tomography (OCT) system is that the optical fiber could be used as a tiny endoscope delivered into the bio-sample for *in vivo* imaging. A variety of probes used in OCT systems have been developed to image tissues in organs such as the colon, esophagus, and blood vessels [1].

It is challenging to fabricate components that rotate the laser beam emitted from a 250 μm optical fiber. Currently, almost all the existing technologies for such rotary scanning probes consist of two basic parts: (1) a coupling component that passes the light from a nonrotating fiber to a rotating fiber and (2) a rotating device that rotates the whole fiber probe. Both of these parts are positioned outside the human body, while only the fiber probe is delivered into the body's blood vessels or other organs. At the one end of the fiber probe, a 90° reflection is introduced to generate a side-viewing beam. The probe scans by rotating the whole optical fiber [2].

A conventional catheter-guided fiber probe has a length of about 1.5 m. Actual experience shows that, as the catheter is inserted into and moved along a constricted passageway such as a blood vessel, the shape of the catheter optical fiber probe becomes twisted and curved. Moreover, the rotation at the distal end of the fiber suffers from nonuniform movements, which produce significant distortion and artifacts in the recorded OCT images [3]. Because these errors happen randomly, it is extremely difficult to calibrate and compensate by post image processing.

To eliminate the need to rotate the distal end of the fiber, methods of using a mirror prism mounted on a micromotor to deflect light radially from a stationary optical fiber have been proposed [4–6]. Two major drawbacks of these designs are wire-shadow effects caused by the motor's electrical wires obscuring a portion of the radial scan and the design and fabrication challenges of miniaturizing the probe along with its complex drive system.

Another type of rotary scanner is based on microelectromechanical systems (MEMS) technology [7–9]. A dual-reflective, single-crystal silicon-based mirror is employed, which can perform half circumferential scans.

Some of the deficiencies in this design are as follows: (1) complexity with the fabrication of the MEMS structures, (2) the light has to be divided to achieve the $2 \times 90^\circ$ scanning range, which requires extra processing steps, (3) the multiple reflections (five) also introduce extra insertion losses, and (4) the relatively large probe size could restrict its use for *in vivo* applications.

We propose to use an *in situ* on-axis rotating mirror to perform the circular scanning, which does not require rotation of the optical fiber cable. Figure 1 shows the design scheme. A commercially available miniature rotary motor, called a squiggle motor [10] (minimum diameter of 1.5 mm), is modified and installed at the distal end of the probe.

The squiggle motor is a new type of motor that provides a cost-effective solution with the following features: tiny size (1/4 to 1/2 the size of other miniature motors), low power consumption (<300 mW), high position resolution (0.5 μm), fast speed (>7 mm/s), and simple design. The squiggle motor consists of four piezoelectric plates bonded to a threaded metal tube with a matching threaded screw shaft. A dual-channel square wave is used to bend the piezoelectric plates to create an orbital “hula hoop” motion in the tube, which causes the threaded screw shaft to rotate and translate. Reversing

Fig. 1. (Color online) Scheme of proposed rotary scanning probe.

the phase shift between the dual-channel waves reverses the direction of the orbit and hence the direction of the screw. These features make the piezoelectric-driven microactuator ideal for biomedical applications.

When the drive signal is applied to the motor, the threaded screw shaft rotates and translates axially (forward/backward) while the optical fiber that passes through the motor shaft remains stationary. A tiny mirror with a 45° reflecting angle is fixed to the motor's rotating screw shaft. As the mirror rotates on the screw shaft, the light emitted from the stationary fiber is reflected 90° outward as a side-view scanning beam. With this setup, novel to our knowledge, beam scanning is smooth and stable without rotating the fiber, and the image is free from wire-shadow effects. In addition, the sensing of weak signals backscattered from structures deep in the tissue is improved due to the avoidance of insertion losses since no optical coupling components are used.

The threaded screw shaft of the miniature motor requires a 0.4 mm diameter hole to be bored along its center axis to allow the insertion of the fiber and its protective steel tube. As the screw shaft traverses back and forth during its rotation, the fiber tip needs to follow the linear motion synchronously; otherwise, the focal distance from the mirror to the sample will change.

A special part called the mirror head cap is designed and fabricated to ensure the fiber moves synchronously with the screw shaft in order to keep a constant distance to the mirror (illustrated in Fig. 2). The head cap's inner thread secures it onto the screw shaft. There are three washers assembled between the screw shaft and head cap. The middle washer made of brass is fixed to the fiber's protective steel tube, while the optical fiber is fixed to the inner bore of the steel tube. When the screw shaft rotates, the head cap moves the steel tube and optical fiber at the same time to maintain a fixed distance to the rotating mirror. The other two washers (made of Teflon) located on each side of the brass washer are used to reduce the rotational friction.

The whole probe is installed within a transparent plastic tube, as shown in Fig. 3. In this prototype, the squiggle motor has a diameter of 1.8 mm, and the catheter has a wall thickness of 0.3 mm.

To test the performance of the rotary probe, we have integrated it with a swept-source OCT system. The swept laser source (HSL2000-HL, Santec) used in the system has a central wavelength of 1320 nm and a full scan wavelength range of 110 nm. The bandwidth of the source corresponds to an OCT axial resolution of $8\ \mu\text{m}$ in the air. The ball-lensed fiber with a lens diameter of

Fig. 2. (Color online) Schematic of mirror head cap. The fiber ball lens is mounted in the center.

Fig. 3. (Color online) Rotary fiber probe with a catheter.

0.30 mm is custom built in-house. It has a focus distance of 1 mm and a spot size of $20\ \mu\text{m}$ in the air. The distance between the top of ball lens and the mirror is $80\ \mu\text{m}$. At a working distance of 1.5 mm, the beam spot size becomes $50\ \mu\text{m}$ in the air (this corresponds to the lateral resolution of the OCT image). The start trigger signal from the swept source was used to initiate the function generator for the rotary scanner and initiate the data acquisition process for each A-scan. Because the swept source was linearly swept with the wavenumber k , A-scan data were obtained by a direct inverse Fourier transformation from the data-acquisition-card-sampled data without performing an additional resampling step.

The first step of integrating the systems involves synchronizing the rotary scan speed of the probe with the OCT system. The motor parameters that need to be set are the duty cycle, frequency, and voltage. The objective is to set the time for one circumferential scan to match the time of one B-scan of the OCT system. The input voltage to the circuit board is set to 3.3 V. The maximum voltage that can be applied to the piezoelectric (PZ) plates is 40 V. For a relatively light load, the voltage can be as low as 20 V. In our experiment, the rotary speed is set to 2 cycles/s and the voltage to approximately 25 V. The second step of integrating the systems is to ensure that the screw shaft returns back to the original linear position after a scan has been performed in one direction.

The experiment was carried out with a phantom vessel as the test sample to simulate the human blood vessel. The phantom mimics not only the arterial shape but also the specific optical and mechanical properties of biological tissue. The phantom is fabricated using a silicon matrix with silica microspheres that, in certain concentrations, imitates the optical scattering effect of tissue [11]. The matrix materials used to fabricate the phantom vessel are very durable and moreover allow the prediction of scattering properties according to Mie theory. By controlling the concentration of silica microspheres at different depths, the phantom [11] can mimic the layered structure (intima, media, and adventitia) of arterial tissue, as seen in Fig. 4. The probe with a measured outer diameter of 2.42 mm is inserted into the phantom vessel, which has an inner diameter of approximately 2.2 mm and a wall thickness of approximately 0.5 mm. The elastic nature of the phantom vessel allows it to stretch and conform to the body of the probe.

Figure 4 shows the result of an OCT B-scan image of the phantom vessel when scanned by the rotary probe.

Fig. 4. OCT images of phantom vessel created by rotary probe. (Top) Image in polar coordinates. (Bottom) Image in X - Y coordinates.

The top image is presented in polar coordinates, and the bottom one is in X - Y coordinates. In the top image, the signals generated (from top to bottom) are from (1) the inner interface of the catheter tube, (2) the first layer of the phantom vessel, (3) the middle layer of the phantom vessel, and (4) the outer layer of the phantom vessel. There is no visible gap shown between the catheter and phantom vessel due to the tight tolerance between them. The wavy appearance of the OCT image in the top part of Fig. 4 is attributed to the misalignment between the rotating center of the probe with the center of the catheter and to the noncircular shape of the phantom vessel and/or catheter tube.

The bottom image in Fig. 4 is generated by a coordinate transformation. This picture clearly shows the cross-sectional structures of the transparent catheter

tube and the phantom vessel. Note that, at the 3:30 o'clock position, there is a small radial shadow. This is caused by a tiny cut mark on the outside surface of the catheter tube, which was made for registration purposes.

In summary, we have developed an *in situ* on-axis rotary probe, which has an unobstructed 360° field of view that does not require rotating a fiber probe or manipulating a MEMS mirror. This design, novel to our knowledge, provides a side-scanning measurement probe system that is accurate, uniform, and stable. Moreover, it avoids unnecessary reflections and optical losses and has almost no time-varying fiber birefringence. To improve the axial resolution, a newly designed ball lens with 1.5 mm focus distance and $27\text{ }\mu\text{m}$ spot size in the air will be used in our next probe. Although only one circular scan was performed in our proof-of-concept prototype, the nature of this design has the capability to produce spiral scanning for three-dimensional volume data. The screw shaft used in our experiment had a thread pitch of 0.16 mm, which is greater than the lateral resolution of the OCT system. However, according to the manufacturer, a finer thread pitch could be obtained. Furthermore, the "pure rotational" version of the squiggle motor with independent rotation and translation control of the probe is also available.

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