Microball lens integrated fiber probe for optical frequency domain imaging

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An integrated microball lens fiber catheter probe is demonstrated, which has better lateral resolution and longer working distance than a corresponding bare fiber probe with diverging beam for Fourier domain optical coherence tomography (FDOCT). Simulation results are shown to gain the effect of the distance between the microball lens and the bare fiber to the focusing plane and beam width. The freedom of modifying the working distance and lateral resolution is shown. This is achieved by changing the gap distance between the single-mode fiber and the microball lens within the packaged surgical needle catheter without using an additional beam expander having a fixed length. The probe successfully acquired cross-sectional images of ocular tissues from an animal sample with the proposed miniaturized imaging probe.

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The challenge of optical coherence tomography (OCT) probe applications generally lies in the development of a sufficiently narrow scanning probe that implements compactly the B-scan mechanism[1,2]. There is also a need for the creation of minimally invasive probes for the high-resolution imaging of intra-organs or tissues[3]. For common-path OCT (CPOCT) systems based on a Fizeau interferometer, the probe works not only as an optical transceiver but also as a reference plane in the conventional Michelson interferometer-based OCT[4]. In this scheme, the probe should provide a moderate level of reflectance for the reference signal as well as the transmittance for the maximum coupling of the back-reflected beam from the object. However, in many cases, bare fibers without any focusing elements have been used to meet the size issue for integration with commercial catheters, where the output beam diverges right after it has been launched from the fiber tip[5,6]. This diverging characteristic not only limits the lateral resolution (beam spot size) but also the working distance. Therefore, the fiber optic probe should be in a very close distance (less than 100 μm) to have an appropriate level of optical signal above the noise[7,8].

To date, there have been several interesting works which include the idea of incorporating micro lenses at the end of a single-mode optical fiber in endoscopic optical imaging[9−12]. Ryu *et al.* introduced a coreless silica-based lens at the tip, which was formed using electric arc discharge of a conventional fusion splicer[9]. Mao *et al.* fabricated a fiber lens based on a graded index (GRIN) lens[10]. Tumlinson *et al.* integrated a micro beam splitter with a reference mirror in a common path system[11]. Yang *et al.* attached a fusion-spliced micro lens at the end of a single-mode fiber (SMF) for side-viewing purpose[12]. In the systems in Refs. [9-11], there is a need for an additional element such as bulk silica[9], fiber spacer[10], and GRIN lens[11] for the beam expansion to achieve enough length for securing the Rayleigh distance ahead of beam focusing. Further, Refs. [9] and[10] are for the conventional Michelson-based OCT configuration which includes an additional reference arm. In this letter, a fabricated micro fiber optic probe incorporating a micro glass ball lens has been used to achieve a longer working distance with a finer lateral resolution for common path optical frequency domain imaging. The axial resolution is determined by the spectral characteristics of the illuminating source. The current work presented the performance of a micro ball lens (diameter: 200–300 μm) probe which has a working distance of a millimeter. The novelty of our work lies in the demonstration of a ball-lens fiber probe for OCT. This is achieved by controlling adaptively the working distance and lateral resolution through modification of the gap between the distal end of an SMF and the micro lens in a needle-based catheter without a fixed inserted bulk element length for securing beam expansion. Finally, the micro ball lens probe was used to obtain clear corneal interface images of a rat eye.

The experimental setup in Fig. 1(a) is based on a simple configuration of CPOCT with a 0.8-μm broadband low-coherent light source (center wavelength: 830 nm, 3 dB width: 40 nm). An optical fiber-based directional two-by-two coupler is used to direct the back-reflected beam to the spectrometer and to connect the input source to the optical probe for scanning. B-scan was performed using a precise sub-micrometer translational stage with a 5-μm step while achieving A-scan from the Fourier transform of the spectrometer output. As shown in Fig. 1(b), the introduced fiber optic probe contains a micro glass sphere lens (diameter: 0.2–0.3 mm, material: BK-7 glass) to focus the diverging beam (initial mode size: 5.7 μm), launched from the tip of the SMF. The components were packaged in a 1-mm (outer diameter) thick, 10-mm long, and 129-μm wide glass fiber ferrule for the insertion

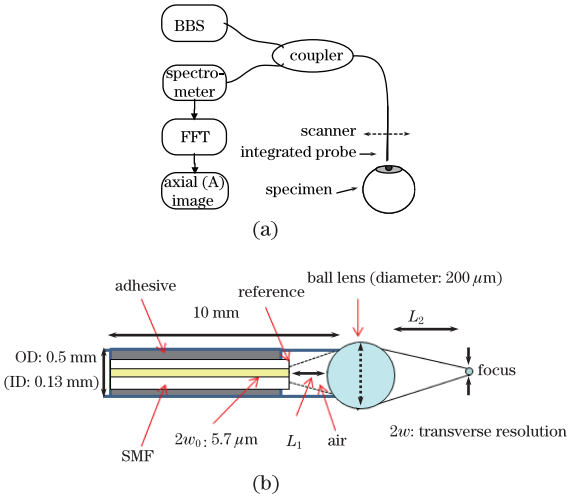

Fig. 1. Experimental setup for Fourier-domain OCT with an integrated micro-lens fiber probe: (a) Fourier domain CPOCT system and (b) integrated micro glass lens probe (BBS: broadband source, FFT: fast Fourier transform, OD: outside diameter, ID: inside diameter).

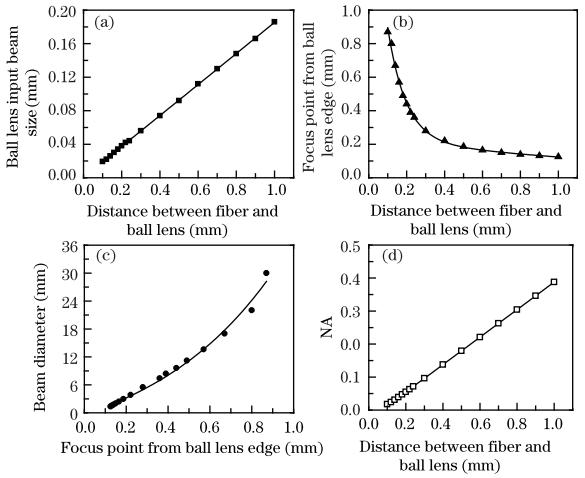

Fig. 2. Estimated performance of the integrated micro ball lens probe: (a) input beam size to the micro lens versus L_1 (distance between the fiber end and the ball lens), (b) L_2 (focus positions) versus L_1 (distance between the fiber end and the ball lens), (c) transverse resolution versus L_2 (focus positions), and (d) NA versus. L_1 (distance between the fiber end and the ball lens).

of a 125-μm bare fiber into a 25–27 gauge metallic needle tube. The reference has been achieved by the fiber tip-air interface due to Fresnel reflection. The ball lens additionally stretches the beam path for imaging by focusing the beam rather than simply diverging after it has been launched from the fiber tip. In this scheme, images can be obtained due to the two surfaces of the ball lens structure. However, the curvature minimizes the coupling of multiple reflections that can occur in between. The microball was simply placed on a U- or V-shaped grooved structure inside the ferrule and cemented by optical adhesive. By controlling the distance between the fiber end and the ball lens (L_1), the position of the focusing point (L_2) and other optical parameters can be varied. The specimen was a 16-week old Long-Evans rat, and the commercial Zemax software was used as an optical system simulation tool.

The beam size entering the ball lens is equal to the diverging beam width determined by L_1 as shown in Fig. 2(a). The result ensures that the beam diameter is less than the micro glass sphere diameter within 1-mm distance. This input beam size would have been the lateral (transverse) beam diameter without a focusing lens, indicating a greater than 40-μm beam size beyond 0.2 mm from the optic probe with beam divergence. Within this L_1 range, as illustrated in Fig. 2(b), the focus positions (L_2) are formed 0.1–1.0 mm away from the lens. This L_1 distance is optimized to obtain both finer transverse resolution and the depth of focus which have a tradeoff relationship (the numerical aperture (NA) is less than 0.4). The estimated transverse resolutions (Δx) at the focus points and their corresponding NA were analyzed using optical beam transfer matrices, as shown in Figs. 2(c) and (d). For less than 1 mm of focusing point, the transverse resolution is smaller than 30 μm, and the depth of focus, which is twice the distance of the Rayleigh range, is 1.8 mm. The NA is related to the transverse resolution as

$$\mathrm{NA} = (2\lambda/\pi)\,(\Delta x)^{-1} = d/2f,$$

where d and f are the input beam size and focal length of the focusing probe, respectively.

Figure 3 shows the obtained images from a thin cover glass slide and a rat eye. The effect of micro lens functioning to generate the focus point in Fig. 3(a) can be clearly observed. Each marked number corresponds to a different position where the slide glass is located to match both front and rear facets. The result indicates that the position at 3 is the focused point having the maximum signal amplitude for the specimen's front and rear layers. In this case, the focused point is formed more than 1.3-mm away. When a bare fiber probe with a diverging beam is used, the probe has to be placed less than 100 μm to the object in order to gain a certain level of object signal and to guarantee transverse resolution depending on the NA of the utilized fiber itself. However, when

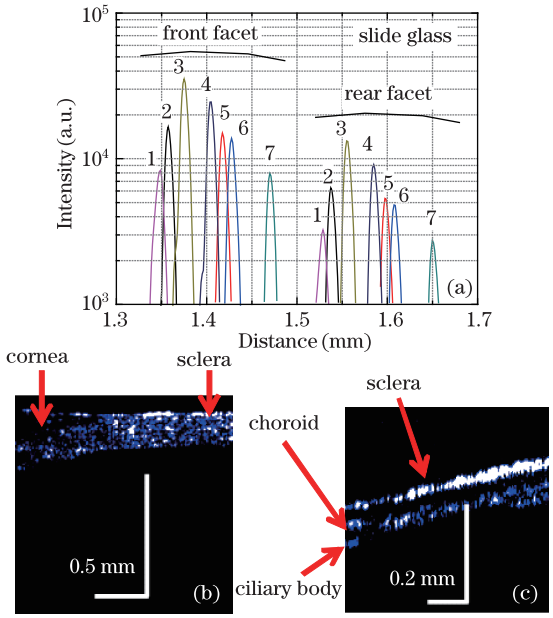

Fig. 3. Obtained sample image results: (a) slide glass (placed in different positions); (b) cornea-sclera interface; and (c) choroid-sclera interface.

the micro lens probe is applied, the working distance is increased to 0.5 mm while maintaining the transverse resolution. The beam diameter is estimated to be approximately 12 μm based on previous analysis. It can be observed that the cornea-sclera interface (Fig. 3(b)) where the left part is the cornea (starts splitting to form a half spherical shape), and the right is the outer sclera surface which is a tough white coating layer forming the framework of the eye. In the other part of the eye near the cornea, the inner choroid-sclera interface with a ciliary body at the end, which is a third separated additional layer (Fig. 3(c)), can be observed. The choroid layer nourishes the eye and backs the retina, and the ciliary body controls the lens shape.

In conclusion, two-dimensional images of an animal ocular morphology are demonstrated. The characteristics of a fiber optic probe incorporating a micro glass ball functioning as a focusing lens is estimated based on common-path optical frequency domain imaging at 0.8 μm. This integration miniaturizes the imaging probe instead of the use of a bulky external lens, and it enables close proximity to the specimen. By controlling the gap between the lens and the fiber, the dynamical extension of the working distance is achievable in millimeter range as well as the transverse resolution in a couple of tens of microns. This is not achievable for a bare fiber having only a diverging beam without a lens element.

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