Observation of Biological Tissues Using Common Path Optical Coherence Tomography with Gold Coated Conical Tip Lens Fiber

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Abstract. In this paper, we proposed a high lateral resolution common-path Fourier domain optical coherence tomography (OCT) system with the use of a chemically etched single mode fiber. In our experiments, single mode optical fiber for 1310nm was used for preparing the tapered tips. Our system used a conical microlens that was chemically etched by selective chemical etching technique using an etching solution of buffered hydrofluoric acid (BHF). From experimental results, we verified that our proposed optical coherence tomography system could operate as a common-path Fourier domain OCT system and conical tip lens fiber was very useful for a high lateral resolution common-path Fourier domain OCT system. Furthermore, we could observe a surface of paramecium bursaria and symbiotic chlorella in the paramecium bursaria using gold coated conical-tip fiber in the water.

1. Introduction
Optical Coherence Tomography is an imaging system which can observe multiple sample’s surface and inside with rapidly as real time microscopic optical-imaging. In this research, we proposed Common Path OCT (CPOCT) for the samples not only in the air but also in high refractive index media such as water. Due to the elimination of the alignment process between the microlens and fiber end, there has been recent interest in developing in-built fiber probes for OCT applications. The advantage of a monolithic conical microlens is only in simple fabrication, but also in generating the back reflected reference signal and providing a capability for focusing the light for imaging without the addition of optical elements.

Axial resolution depends on only the center wavelength and bandwidth of the light sources, so we set up a goal that is to improve lateral resolution using SLD with a center wavelength of 1310nm and bandwidth of 70nm. It is needed to narrow down the beam diameter for improving lateral resolution. For that reason, using an optical lens was commonly way. However, there were problems that it made OCT system be bigger and a beam diameter spread very immediately. Therefore we proposed a conical microlens that was chemically etched in the core at the fiber tip[1][2]. Furthermore, we tried to use CPOCT in high refractive index media, like blood vessel identification. CPOCT using conical-tip could not be functioning in high refractive index media such as water because the value of back-reflected light field from the conical tip was too low. For this reason, we had to set reference intensity at a high level by coating the tip with a thin layer of gold. From experimental results, we verified that conical-tip fiber coated with a thin layer of gold could be operated as a fiber probe of...
CPOCT with high lateral resolution. Furthermore, we could observe a surface of paramecium bursaria and symbiotic chlorella in the paramecium bursaria using gold coated conical-tip fiber in the water.

2. Chemically etched single mode fiber tip
A fiber can be sharpened by utilizing the difference in etching rate between its core and cladding when immersed in an etching solution of buffered hydrofluoric acid (BHF), a mixture of 50% weight hydrofluoric acid (HF) and 40% aqueous solution of ammonium fluoride (NH₄F).

![SEM images of optical fiber axicon microlens](image1)

Fig. 1. SEM images of optical fiber axicon microlens. The volume ratio of NH₄F:HF is 2:1. (a) The apex angle is 126deg. (b) Tilted SEM image of (a).

To make an axicon lenses, we prepared etching solutions. They were mixtures of NH₄F versus HF by volume ratio of 2:1. A cleaved fiber was immersed in the 2:1 BHF etching solution for 30min. The fiber used for fabrication was a standard single-mode fiber with an MFD of 9.5μm at λ=1310nm. Then axicon microlens was formed at the cleaved fiber. Fabricated axicons had apex angles of 126deg for 2:1 solution as shown in Fig. 1. We also studied the laser beam profiles emanating from the fiber probe by objective-lens imaging experiments.

Figure 2 shows two dimensional intensity profiles at the beam waist for (a) cleaved fiber and (b) 126deg axicon respectively. The central spot size is ~9.5μm for cleaved fiber and ~3.2μm for 126deg axicon with 1310 nm wavelength light-source. Table 1 shows the beam diameter as a function of the distance from beam waist(Z=0μm). From these results, we could verify that beam diameter emerging from axicon fiber was smaller than that emerging from cleaved fiber.

![CCD camera images of field distribution](image2)

Fig. 2. CCD camera images of field distribution at the beam waist for (a) cleaved fiber and (b) 126 deg axicon fiber, respectively.
3. Experimental setup

The experimental setup of the common-path FD-OCT setup is shown in Fig. 3. The low coherence light source was a superluminescent diode (SLD) (Denselight Semiconductors) with a centre wavelength of 1310nm and spectra width of 70nm. A commercial spectrometer (B&W Tek Inc.) was used. The optical power, from the conical-tip fiber probe, incident on the sample was measured using a photo-detector (PDA10CS, Thorlabs Inc.) to be approximately 1mW. The motorized translation stage (KT-LS13-M, Zaber Technologies Inc.) provided the lateral scanning for the B-scan operation. A custom program was written with Labview version 8.2 (National Instruments) to operate and collect data from this experimental CPOCT system.

![Experimental setup diagram](image)

Fig. 3. Schematic of the in-fiber CPOCT setup incorporating the conical-tip fiber probe.

4. Experimental results

The lateral resolution of the 126deg conical-tip fiber was measured using an USAF resolution target card (Edmund Optics). The target card is made up of different rectangular gratings with different widths. For example, the line pairs for elements E2 and E6 of group 6 are 13.9μm and 8.8μm respectively. This implies that the corresponding thickness of each line in E2 is 6.95μm and the corresponding thickness of each line in E6 is 4.40μm. The scanning was carried out at a lateral step size of 0.1μm and with the fiber end positioned 30μm away from the target card. A cleaved fiber, using the same experimental setup as in Fig. 3, was used for comparison. From our previous work, it was found that the 126deg conical-tip fiber was able to clearly resolve the lines in element E6 of group 6 whereas the cleaved fiber was barely able to. From these results, we can verify that 126deg axicon
fiber has higher resolution than that of the cleaved fiber. We also investigated the lateral resolution of the system at 100μm and 250μm away from the target card. Experimental results were shown in Fig. 4 and Table 2.

![Graph](https://via.placeholder.com/150)

**Fig. 4.** Lateral plot of a single scan OCT data using 126deg axicon fiber. (a) 100μm away from the target card (group 5). (b) 250μm away from the target card (group 4).

**Table 2.** Measured lateral resolution of 126deg conical-tip fiber

| Distance $D_z$ | 30μm | 100μm | 250μm | 600μm |
|----------------|------|-------|-------|-------|
| **Resolution** | 4.4μm | 8.77μm | 12.4μm | 16.0μm |

$D_z$: Distance between fiber probe and target card

Table 2 shows the measured lateral resolution as a function of the distance between fiber tip and target card. Generally the depth range is limited by the wavenumber spacing between pixels of the spectrometer. So, we also investigated the lateral resolution of the system at the extreme end of our depth range (0.6mm from the fiber tip) where we found that the lateral resolution of our 126deg fiber decreased to ~16μm. According to these results, we could verify that chemically etched axicon fiber was useful for a high lateral resolution common-path Fourier domain OCT system. To demonstrate the imaging capability of the conical-tip fiber through the common-path technique, a two dimensional
cross sectional scan of a sample of leaf was performed. Figure 5 depicts a cross-section OCT tomogram of the leaf sample obtained with the conical-tip fiber. The step-size set on the translation stage used for the scanning was 2μm step. The cell wall layer making up the epidermis layer is clearly evident from the rest of the section. In addition the vascular bundle, which plays the vital role of transporting nutrients to the surrounding tissue, can also be observed in the tomogram.

![Image of cross-section OCT tomogram](image1.png)

Fig. 5. A cross-section OCT tomogram of the leaf sample using the conical-tip fiber in the CPOCT setup.

Furthermore, we tried to use CPOCT in high refractive index media, like blood vessel identification. CPOCT using conical-tip could not be functioning in high refractive index media such as water because the value of back-reflected light field from the conical tip was too low. For this reason, we had to set reference intensity at a high level by coating the tip with a thin layer of gold. Figure 6 shows the measured signal to noise ratio (SNR) as a function of axial distance between the conical-tip fiber end and mirror for 126deg axicon. The SNR was obtained by using the peak signal of the mirror surface in water solution, after inverse Fourier transform, over the noise floor. The SNR > 30dB is achievable at an axial distance of 0.5mm from the fiber tip.

![Graph of signal to noise ratio](image2.png)

Fig. 6. Measured signal to noise ratio with the 126deg gold coated conical-tip fiber for different axial position between the fiber tip and mirror in water.
Figure 7(a) depicts the bright-field image of the paramecium bursaria. The dotted line indicates the scan path. We can see the symbiotic Chlorella in paramecium bursaria. We pretreated the paramecium using NiCl$_2$ solution, in which paramecia stopped the action of cilia. So the paramecium bursaria did not move. A cross-section OCT tomogram of the paramecium bursaria was shown in Fig. 7(b). We could observe a surface of paramecium bursaria and symbiotic chlorella in the paramecium bursaria using gold coated conical-tip fiber in the water. From these experimental results, we verified that conical-tip fiber coated with a thin layer of gold could be operated as a fiber probe of CPOCT with high lateral resolution.

Fig. 7. (a) Image of paramecium bursaria with NiCl$_2$ solution. The paramecia stop the action of cilia. (b) A cross-section OCT tomogram of the paramecium bursaria using the conical-tip fiber in the CPOCT setup.

5. Conclusions
In this paper, we proposed a high lateral resolution common-path Fourier domain OCT system with the use of a chemically etched single mode fiber. The conical-tip fiber could be readily fabricated via a selective-chemical etching technique at low cost and with high reproducibility. From experimental results, we verified that our proposed optical coherence tomography system could operate as a common-path Fourier domain OCT system and conical tip lens fiber was very useful for a high lateral resolution common-path Fourier domain OCT system. Furthermore, we could observe a cross-section OCT tomogram of the paramecium bursaria using the gold coated conical-tip fiber in the CPOCT setup.

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