Experimental and Theoretical Investigation of Common Path Optical Coherence Tomography Using Conical Tip Lens Fiber

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Abstract. We proposed Common Path Optical Coherence Tomography (CPOCT) using gold coated conical tip lens fiber with a central wavelength of 1310 nm SLD to improve lateral resolution under the water. We already verified that conical tip lens fiber was good to improve the lateral resolution in CPOCT in air. However, CPOCT using conical tip lens fiber could not be functioning under the water solution 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. Then, we could have the right balance of reference intensity and sample intensity with gold coated conical tip lens fiber. Furthermore, the results of beam diameter, SNR, lateral resolution show that gold coated conical tip lens fiber is better than cleaved fiber. Then, we could observe two dimensional cross sectional scan of samples, for example, fresh leaves under the water by CPOCT using gold coated conical tip lens fiber.

1. Introduction
Optical Coherence Tomography (OCT) is an imaging system which can observe multiple sample’s surface and inside with rapidly as real time microscopic optical imaging. OCT is also able to provide non-invasive imaging of living tissues and organisms with high-resolution. OCT is based on low-coherence optical interferometer principles. The way of imaging with OCT is using contrast of the light scattering properties of samples. OCT uses near-infrared region light source because that wavelength decreases scatter. In other words, OCT can image the deeper axial position of samples than using shorter wavelength. For this reason, OCT has already put to practical use in medical institution, so it is easy to expect to develop improvement medical instruments [1].

Original OCT technique is firstly developed as Time Domain OCT (TDOCT), however, Fourier Domain OCT (FDOCT) has been used extensively because of its advantages which are high sensitivity and high imaging speed. This advancement also made OCT be more high-resolution. Axial resolution depends on only the center wavelength and bandwidth of the light sources. Broad bandwidth light sources improve it in OCT because they can reduce the coherence length [2]. From this reason, we set up a goal that is to improve lateral resolution. That is needed to narrow down the beam. For that reason, using an optical lens is commonly way. However, there are problems that it makes OCT system be bigger and beam diameters spread very immediately.

High-resolution in OCT also has problems. It is that the difficulty of dispersion mismatch between sample and reference arm is caused by handling long optical fibers. That is to say, polarization fading, temperature, pressure, optical fiber bending and so on make problems. These problems can be resolved by controlling reference arm and sample arm reflectance independently. Therefore, we chose a common-path design OCT (CPOCT) whose sample and reference arm share the same optical path.
[3]. Typical FDOCT takes reference beam from the reference mirror but CPOCT get it from the optical fiber tip. This CPOCT has many advantages [4]. Firstly, the dispersion and polarization mismatch of typical OCT’s two optical paths (reference and sample arm) are automatically eliminated. Secondly, CPOCT can be a high-speed transport system and decrease the vibrations sensitivity. Finally, CPOCT is smaller than typical OCT because there is only one optical path to samples.

To improve the lateral resolution in CPOCT, we should narrow down the beam diameter from the optical fiber tip. On this account, we used a conical microlens that was chemically etched. We processed the optical fiber tip by a buffered hydrofluoric (BHF) etching solution, which was used in the selective-chemical etching technique. These processed optical fibers are called conical tip lens fiber. We already verified that conical tip lens fiber was good to improve the lateral resolution in CPOCT in air [5].

In this paper, we aimed to use CPOCT which was an invention with many potential uses in high refractive index media, like in vivo and blood vessel identification [6], [7]. Nonetheless, CPOCT using conical tip lens fiber 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 [8], [9]. And so, we could have the right balance of reference intensity and sample intensity by this thin layer of gold coated conical tip lens fiber.

We also investigate the theory of conical tip lens fiber’s beam propagation with the finite-difference time-domain (FDTD) method. The FDTD method is an efficient way to propose the full-wave analysis from fiber tip [10], [11]. Then, we demonstrated the conical tip lens fiber availability by CPOCT experiments and simulation of the FDTD method.

2. Experimental Setup

The proposed setup is shown in Figure 1. The light source, we used is, superluminescent diode (SLD) (DL-BX9-CS3089A, DENSELIGHT). The SLD generates light at center wavelength of 1310nm and full width at half maximum (FWHM) is 70nm. The light source is fed into the optical circulator (CIR-1310-50-APC, THORLABS) which allows light to travel in only one direction. And then, the light emitted from the optical circulator into the common-path interferometer through a single-mode optical fiber (P3-SMF28-FC-5, THORLABS). The optical fiber which goes on sample is fixed on a pole, and the pole is also on the Linear Stages (T-LS13M, Zaber Technologies Inc.) for scanning the sample in the x direction. The light from the sample arm is coupled into Fiber Optic Coupler (FC1310-70-50-APC, THORLABS), then is detected by the spectrometer (BTC 261E, B&W Tek Inc.) and Photodetector (PDA10CS, THORLABS). The spectrometer has 0.77nm wavelength resolution. We can get the OCT image by LabView on PC. Our experience is used the SLD which gives ~11μm axial resolution, however we focused on the lateral resolution by using conical tip lens fibers.

The SEM image in Figure 1 shows conical tip lens fibers and their tips. This conical tip lens fiber is processed by a buffered hydrofluoric (BHF) etching solution which is used in the selective-chemical etching technique with a volume ratio of NH₄F: HF, respectively as 2:1. This proceeded conical tip lens fiber has better lateral resolution [5]. We maintained a volume ratio of 2:1 and the solution temperature which is 40 degree Celsius constantly.
3. Theoretical Simulation

We also investigated the beam propagation with the FDTD method. The FDTD method has the direct solution to the Maxwell’s time-dependent curl equations numerically, and, discretizes the space and time into rectangular cells and intervals, respectively. Then, the time variations of the field components at each cell.

To demonstrate FDTD computation, we considered that the simulation box consists of a 360,000 (400x900) grid in the x and y directions and the total number of the time steps is 3,500. We verified that conical tip lens fiber could be used instead of a conventional focusing lens to achieve both high lateral resolution and a long depth of focus simultaneously[12]. We could validate that conical tip lens fiber achieved a long depth of focus even under the water.
4. Results and discussion

We fabricated a conical tip lens fiber using a 2:1 BHF solutions yielding a cone angle of 129 degree. Before experiments of OCT imaging, we measured beam diameters from cleaved fiber and conical tip lens fiber under the water. Table 1 shows the beam diameters whose distances were beam waist, then, beam waist plus 10μm, 20μm and 30μm. According to these numerical values, conical tip lens fiber could narrow down the beam diameters than cleaved fiber. From these results, we used conical tip lens fiber for CPOCT in high refractive index media. Since the value of back-reflected light field from the conical tip was too low under the water, we coated the conical tip lens fiber with a thin layer of gold. Then, the value of back-reflected light field was about 155times as higher value, which was 0.46%, as non coated conical tip lens fiber.

Table. 1. The spot sizes of cleaved fiber and conical tip lens fiber under the water.

|               | Beam waist | +10μm | +20μm | +30μm |
|---------------|------------|-------|-------|-------|
| Cleaved fiber | 9.3μm      | 9.8μm | 10.1μm| 10.5μm|
| Conical tip lens fiber | 7.2μm | 7.2μm | 7.6μm | 8.6μm |

Figure. 3. CCD camera images of field distribution at the beam waist under the water of: (a) cleaved fiber; (b) conical tip lens fiber; (c) gold coated conical tip lens fiber, respectively. The central spot sizes are (a) 9.3μm, (b) 7.2μm and (c) 6.2μm with 1310nm wavelength light source, respectively.

We also measured the beam diameter of gold coated conical tip lens fiber as Figure. 3. They show the pictures of beam waist diameters. According to these pictures, the beam waist diameter of cleaved fiber is the largest (Figure. 3. (a)) and gold coated conical tip lens fiber is smallest (Figure. 3. (c)). That is to say, gold coated conical tip lens fiber could narrow down the beam diameter the most under the water. We did some experience with this gold coated conical tip lens fiber. Figure. 4 shows SNR whose axial positions are between the gold coated conical tip lens fiber tip and sample as mirror (150-500μm) under the water with constant power of 0.5mW at fiber tip. We could keep the SNR more than 30dB even at the position of 500μm. Therefore, gold coated conical tip lens fiber has right balance of reference intensity and sample intensity.
Figure 4. SNR where the axial positions of 150-500μm under the water.

Figure 5. Experimental results. (a) fringe pattern; (b) inverse Fourier transform of mirror; (c) Comparison of experimental and theoretical axial resolution results, respectively.

To compare experimental results and theory of axial resolution, we took data of a mirror. Figure 5. (a) shows spectral fringes with mirror as the specimen. Figure 5. (b) is an inverse Fourier transform of Figure 5. (a), after performing k-space interpolation on Figure 5. (a). Axial resolution measured with gold coated conical tip lens fiber under the water by Figure 5. (b) was 9.95μm, and other axial position between optical fiber tip and a mirror is shown in Figure 5. (c). We also calculated axial resolution by theoretical way and the equation is given by [13].
\[
\delta z = \frac{2 \ln 2}{\pi} \frac{\lambda_0^2}{n \Delta \lambda},
\]

where \(\lambda_0\) is the center wavelength, \(\Delta \lambda\) is the FWHM and \(n\) is the group refractive index. We used SLD whose light at center wavelength of 1310nm and FWHM is 70nm under the water (\(n=1.33\)). Then, as Figure. 5. (c) showing, the calculated theoretical axial resolution was 8.13μm. We considered that the difference between experiment and theory is due to optical aberrations in the optics. We note that these experiments were carried out in optical fibers. The resolution would be improved by a factor of \(n\) in the medium.

After measuring axial resolution, we compared with cleaved fiber and gold coated conical tip lens fiber by lateral resolution. We used 1951 USAF Resolution Target (NT38-257 Edmund optics) as a sample to examine lateral resolution. According to Figure. 6. (a), cleaved fiber could not scan 3rd element clearly, however, gold coated conical tip lens fiber could even at 5th element. That is to say, at the axial position of 30μm between the fiber tip and the sample, gold coated conical tip lens fiber has better lateral resolution than cleaved fiber. Figure. 6. (b) also shows that cleaved fiber could not any element while gold coated conical tip lens fiber could do 2nd element at the axial position of 150μm. These results mean that using gold coated conical tip lens fiber improved lateral resolution than cleaved fiber, even at the distant axial position.

![Figure 6. Lateral resolution comparison with cleaved fiber and gold coated conical tip lens fiber: (a) the axial position which is from gold coated conical tip lens fiber to the sample was 30μm; (b) the axial position was 150μm, respectively.](image)

We used this gold coated conical tip lens fiber to scan OCT image under the water. For example, we scanned a leaf which is under the water like Figure. 1’s sample part. The result of scanning a leaf is shown in Figure 7. We could observe the leaf facing and its ducts clearly by CPOCT using gold coated conical tip lens fiber.
5. Conclusion

We proposed CPOCT using gold coated conical tip lens fiber with a wavelength of 1310 nm SLD to improve lateral resolution under the water. Using gold coated conical tip lens fiber, we had to set reference intensity at a high level, and we could have the right balance of reference and sample intensity. Furthermore, lateral resolution from our experimental results mean that gold coated conical tip lens fiber improved it clearly than cleaved fiber. Those results also show that our gold coated conical tip lens fiber has high lateral resolution and a long depth of focus. And then, we could observe two dimensional cross sectional scan of samples, for example, fresh leaves under the water by CPOCT using gold coated conical tip lens fiber. From our experimental and theoretical studies, it was found that gold coated conical tip lens fiber could be used instead of a conventional focusing lens to achieve both high lateral resolution and a long depth of focus simultaneously in CPOCT under the water.

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Figure. 7. Two dimensional cross sectional scan image of a fresh leaf under the water.
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