Dual-channel spectral-domain optical-coherence tomography system based on 3 × 3 fiber coupler for extended imaging range

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We have demonstrated a dual-channel multiplexing spectral-domain optical-coherence tomography (SD-OCT) system based on a 3 × 3 fiber coupler for extended imaging range of whole human eye depth, with a single light source and spectrometer. OCT images of anterior segments of a human eye were sequentially performed and constructed to demonstrate an extended depth range as large as 15 mm in air. A good quality OCT image of the whole anterior segment of an eye was present. Furthermore, whole eye segmental imaging was performed and ocular distances were calculated to show the validation of the system for whole eye morphological measurement. © 2014 Optical Society of America

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1. Introduction

Eye diseases such as age-related macular degeneration (AMD), retinal pigmentation, and glaucoma can significantly affect the life quality of patients. The diseases can alter the physical shapes and structures of different segments of the whole eye; therefore in situ, noninvasive tomographic imaging diagnosis with high sensitivity is favorable. It is especially important to image both the anterior and posterior of the eye simultaneously for diagnostic purpose. Of the current ophthalmologic clinical technologies, ultrasound, magnetic resonant imaging, and optical-coherence tomography (OCT) have been widely used. On one hand, as the resolution of current high-frequency ultrasound imaging is limited to 0.1 mm with poor contrast, it can only be applied in the ocular vascular imaging [1]. A high-resolution MRI can be applied for eye imaging also, yet the trade-off between the resolution and imaging depth prohibits it from imaging the entire eye with high resolution sufficient for diagnosis [2]. In addition, the size and cost of an MRI also hinders it from being portable or practical for routine diagnosis.

On the other hand, optical techniques such as OCT have been rapidly developing as a noninvasive technique that provide high-resolution cross-sectional...
images with large imaging depth \([3,4]\). With the development of light source and taking advantage of the vertical-cavity surface emitting laser (VCSEL) technology, swept-source OCT (SS-OCT) takes a great step by extending the imaging range to whole eye segments depth \([5]\). The standard clinically used spectral-domain OCT (SD-OCT), which provides the significant advantage of higher resolution and increased phase stability for functional imaging, is limited to the imaging of the anterior segment of the eye or retina. This is because the imaging depth range is restricted by the finite resolution of the spectrometer and the signal-to-noise ratio (SNR) fall-off with the scan depth \([6–8]\). In ophthalmology, the largest depth range of the clearly differentiable images obtained by the conventional SD-OCT system is reported to be about 7 mm in air \([9]\).

To resolve the restrictions researchers have been engaged in increasing the imaging depth by increasing the spectral resolution in the spectrometer \([6]\), utilizing full-range complex (FRC) imaging techniques \([10–12]\), or using a fast switching approach \([13,14]\). Through the combination of dual-channel Michelson interferometer OCT systems focusing on different segments of the eye, we have achieved the whole anterior eye segment and whole eye segment imaging \([15,16]\). The systems consist of two identical OCT setups aiming for the imaging of both anterior and posterior segments of the sample. In this work we present a new design of the SD-OCT system capable of deep imaging depth by multiplexing one OCT light source and one detector. A \(3 \times 3\) fiber coupler is employed for the OCT signal acquired from different segments, which are determined by two reference distances. Extended depth imaging of the anterior segment of the human eye was performed and high-quality OCT imaging was demonstrated with an imaging depth as large as 15 mm in air. Furthermore, the \textit{in vivo} whole eye segment imaging was demonstrated by using this dual-channel SD-OCT system and ocular distance measurement was presented.

2. Experimental Setup and Signal Processing

A. System Configuration

The schematic of the dual-channel SD-OCT system based on a \(3 \times 3\) fiber coupler is shown in Fig. 1. One of the three arms on the input side of the fiber coupler (AC Photonics, Inc., Single Fusion \(3 \times 3\) Coupler) is used to couple light into the two interferometers, while a second arm is used to couple the light returned from the reference and sample arms into a spectrometer. The third arm is not connected. On the output side of the fiber coupler, one arm is used to establish the sample arm of the measurement system, while the other two arms are used to establish reference arms. In this dual-channel system, channel 1 comprises the sample arm and the upper reference arm, and channel 2 comprises the sample arm and the lower reference arm. In the sample arm, light beam coming out of the sample fiber is scanned by the XY galvanometer scanner, which is mounted on an XYZ translation stage for correctly adjusting the scanner position to achieve a \(\pi/2\) phase shift between adjacent A-scans for FRC imaging \([12]\). Then the light beam is focused on the anterior segment of the eye by an objective lens \((f = 100\) mm). To obtain an extended depth range image, human eyes from healthy volunteers have been imaged. Experiments are performed as follows: reference arm 1 was first adjusted so that the anterior segments of the eye and the overlapping mirror sections could be imaged. Then reference arm 2 was adjusted behind the rear segment of the sample (for the anterior segment of eye imaging, the rear segment of the sample is the rear segment of the lens, and for whole eye segment imaging, the rear segment of the sample is the retina) to ensure that negative and positive optical path differences with respect to the reference mirror can be distinguished. Interferogram 1 is achieved in interference 1 by closing the lower reference arm 2 using a shutter to prevent the generation of an unnecessary interference signal, and the interferogram 2 is achieved in interference 2 by closing the upper reference arm 1. The distance between the two OCT images was then measured with a mirror as a sample, which was mounted on a translation stage in the sample arm. Knowing the distance between the images, a composite cross-sectional image can be finally constructed from them. Thus, all the surfaces of the sample segment can be imaged with the two OCT sub-channels.

The spectrometer is designed for the imaging depth range of 7.5 mm in air. The super-luminescent diode-based light sources (SLD) (Inphenix, USA) with FWHM bandwidths of 45 nm is used, with the center wavelength of 840 nm, the calibrated depth resolution is 7 \(\mu\)m in air. The linear CCD cameras (Aviiva-SM2-CL-2010, 2048 pixels with 10 micron pixel size, operating in 12 bit mode, e2V) in the spectrometer are operated at a rate of 24 k lines per second. The sensitivity decreased from 101 dB at the zero-delay plane to 70 dB at the maximal imaging depth. The lateral resolution is 43 \(\mu\)m. The exposure power in front of the eye is 1.8 mW, which is safe for long exposure to the eye according to ANSI Z136.1.
B. Signal Reconstruction

Fused-fiber couplers rely on evanescent-wave coupling to split an input electric field between output fiber paths, according to coupled-mode theory [17]. In the Michelson interferometers using an AC Photonics 3 × 3 truly fused-fiber coupler, as illustrated in Fig. 1, the coefficient of power transfer from light-input fiber a to output fiber b (α_{ab}) is about α_{11} ≈ α_{12} ≈ α_{13} ≈ 1/3. After the round-trip reflection from the reference and the sample arms, the detected interference signal at the spectrometer may be expressed as

\[ I(k, x) = I_r(k, x) + 2\sqrt{I_r(k, x)I_s(k, x)} \sum_n a_n \cos(kx) + I_s(k, x), \]  

(1)

where \( I_r(k, x) \) and \( I_s(k, x) \) are the wavelength-dependent intensities reflected from the reference and sample arms, respectively, and \( k \) is the wave number and \( x \) is the transversal scanning direction. \( a_n \) is the square root of the sample reflectivity at depth \( z_n \).

For reconstruction of the image of channel 1, the FRC process is applied. Before reconstruction of the image, fixed noise and DC were first removed. The flowchart, the solid line section in Fig. 2, shows the same data set with FRC post-processing. The object structure is disturbed by overlapping of mirror images. Figure 3(b) shows the same data set with FRC post-processing. We can see that the imaging depth range is from the front surface of the cornea to the anterior segment of the lens. The quality of the image is good, the epithelium of the cornea and strongly backscattered intensity within the lens can be observed, as well as the lens capsule, which is clearly visualized.

Figure 3(c) shows the image of the rear segment of the lens, which is obtained in the channel 2 of the dual-channel SD-OCT system. As we can see from Fig. 3(c) the strongly backscattered intensity within the lens can be observed, and the lens capsule is clearly visualized. In this channel, since the fixed noise and DC removal, depth profiles of the rear segment of the sample is reconstructed by a Fourier transform of the spectral interferogram results in the OCT B-scan image \( I(z, x) \), which is displayed on a logarithmic gray scale [16].

Finally, the whole image of the sample can be constructed in scale. Details are as shown in [16].

3. SD-OCT for Human Eye Imaging

A. OCT Imaging of the Anterior Segment

Experiments of the anterior segment of eye imaging are performed in vivo using the left eye of a healthy volunteer (21 years old, male, he fixates his left eye on a letter chart through fixating setup). The measured distance between two OCT images is about 6.110 mm in air. In channel 1, in order to suppress the negative effect of the sensitivity fall-off with depth increasing, the reference arm 1 is placed onto the position that the zero path difference engenders in front of the iris. Figures 3(a)–3(d) show the images obtained in two sub-channels and their constructed image of the anterior segment of eye. Figure 3(a) shows a SD-OCT image obtained by inverse fast Fourier transform of the spectral interferogram without applying FRC reconstruction. The object structure is disturbed by overlapping of mirror images. Figure 3(b) shows the same data set with FRC post-processing. We can see that the imaging depth range is from the front surface of the cornea to the anterior segment of the lens. The quality of the image is good, the epithelium of the cornea and strongly backscattered intensity within the lens can be observed, as well as the lens capsule, which is clearly visualized.

Figure 3(c) shows the image of the rear segment of the lens, which is obtained in the channel 2 of the dual-channel SD-OCT system. As we can see from Fig. 3(c) the strongly backscattered intensity within the lens can be observed, and the lens capsule is clearly visualized. In this channel, since the
reference arm 2 is placed to the position that the zero path difference appears behind the rear segment of the lens, the strongly scattering iris is blurred due to the image quality degeneration with the distance increasing.

Finally, the whole segment of the anterior eye is constructed into one image in scale. As shown in Fig. 3(d), the whole depth of the anterior segment of the eye could be imaged and the image quality is satisfactory for practical measurement.

B. OCT Whole Eye Segment Imaging

In whole human eye imaging in vivo, a normal left eye with myopia (~7 diopters) was imaged. The reference arm 1 was placed on the position where the zero-path difference is formed just behind the iris to obtain the complex conjugate of the OCT signal of the anterior segment of the eye. The reference arm 2 was placed behind the retina. The measured distance between the two OCT images was 29.531 mm in air. In the computer simulation (Zemax) performed by using a Navarro eye model, the spot diameters were about 86 μm at the cornea and 394 μm at the retina, respectively.

Figures 4(a)-4(d) show the two images, one combined image and an A-line signal image. Figure 4(a) demonstrates the result achieved with whole anterior segment imaging using FRC postprocessing method. The whole anterior segment of the eye is imaged from the front surface of the cornea to the posterior surface of the lens.

From Fig. 4(b) we can see that the retina image is clearly visualized. Since the probe beam is focused in the anterior segment of eye, the beam spot size at the retina increases due to the refraction of the eye, which decreases the transversal resolution. Since a telecentric raster scanning is used in this system, the diameter of retina imaged is about that of the pupil and other portions of light are blocked by the iris. Figure 4(c) shows the image of the whole eye segment from the anterior chamber and crystalline lens to the retina, in which a gap between two channels is filled with blank, which indicates the space of the vitreous body.

By using the whole eye segment image, the intraocular distances after correcting for the refractive index of each ocular component can be measured [14]. As shown in Fig. 4(d), the A-line signal is a plot to identify the central reflexes of the anterior and posterior surfaces of the cornea, and the anterior and posterior interfaces of the crystalline lens and retina. By using the intensity peaks, the biometric distance of the eye is calculated as shown in Table 1, which validates the capability of this system for whole eye morphological measurement.

### Table 1. Ocular Distance Measurements using a Dual-Channel OCT System Based On 3×3 Fiber Coupler

<table>
<thead>
<tr>
<th>Biometric Parameter</th>
<th>Dual-Channel OCT System (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central corneal thickness</td>
<td>0.52</td>
</tr>
<tr>
<td>Anterior chamber depth</td>
<td>2.83</td>
</tr>
<tr>
<td>Lens thickness</td>
<td>5.01</td>
</tr>
<tr>
<td>Axial eye length</td>
<td>24.3</td>
</tr>
</tbody>
</table>

4. Conclusion and Discussion

SD-OCT has been rapidly developed for ophthalmic imaging ever since it was invented. Commercially available SD-OCT devices have limited image depth up to 7 mm, which is not sufficient for the anterior segment of eye imaging, let alone whole eye segment imaging. By using the dual-channel SD-OCT system based on a 3×3 fiber coupler, both imaging of anterior segment of the eye with good contrast and imaging of the whole eye segment are realized. Compared with the dual channel SD-OCT system, which uses a two-light source and two spectrometers [18]; the 2×2 fiber-coupler fast-switching approach [13,14]; the frequency multiplexed method equipped with acousto-optic deflectors [18]; and the system using coherence revival of the light source [19], this system uses a conventional SLD light source and simple system equipment to obtain an image of the whole eye segment. The equipment cost is dramatically lower, the system complexity is reduced, and the system stability is increased, which make this approach applicable to field diagnosis.

Compared with the image quality of the SS-OCT using VCSEL technology, some degradation of image quality in this system is induced by the SNR fall-off with the scan depth and the beam separating in the fiber couple. As we can see in the whole eye segment
imaging obtained in this system, the upper part of the cornea and the rear segment of lens are not clearly visible. But compared with that obtained in the dual-channel dual-focus SD-OCT system [15], the frequency multiplexed method is equipped with acousto-optic deflectors [18] and the system using coherence revival of the light source [19], the quality is obviously improved. The interfaces of whole eye segments can be easily discriminated and the biometric distance of the eye can be appropriately calculated, which provides sufficient information for diagnosis of a variety of eye diseases.

The advantage of this dual channel OCT lies on its long imaging range and simple configuration. As a compromise, the lateral resolution performance is decreased using a single-focus beam in this system. In our system, the focal spot has a diameter of about 43 μm. The beam diameter becomes substantially larger when going deeper in the eye, which decreases the transversal resolution of the retinal image. Furthermore, the image of the retina obtained with the current telecentric scanning configuration is a plane line that represents a narrow transversal region of the retina. As a result, the OCT image of the retina obtained in this system cannot provide wide-field structural information. Only the fovea area, which is the most sensitive region for AMD, can be imaged. However, the high-intensity signal produced by the retina adequately ensures the measurement of the axial eye length.

In this dual-channel SD-OCT system, the whole segment of the sample is constructed by the successive received interference signals in sub-channels. To further increase the multiplexing speed for clinical applications, electronic modulation can be applied to replace the mechanical shutter. Furthermore, for accurate clinic measurement, a distortion correction algorithm needs to be implemented in the signal processing for quantitative biometry of the ocular surfaces.

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