Parallel optical coherence tomography using a CCD camera

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Parallel optical coherence tomography is demonstrated using a 12-bit scientific-grade charge-coupled device array. A superluminescent diode in combination with a free-space Michelson interferometer was employed to achieve 10-μm axial resolution and 1.1-μm transverse resolution on a 902×575 μm^2 field of view. We imaged a test mirror and bovine retinal tissue using a four-step phase shift method.

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Optical coherence tomography (OCT) is a very effective way to produce micrometer-resolution images[1−4] from deep within translucent or scattering media like the retina and other biological tissues, and it is widely held to be one of the most promising high resolution, noninvasive imaging modalities for medicine. OCT uses short coherence light source and Michelson interferometer to enhance axial resolution and to discriminate against scattered light. OCT is usually implemented in a fiber-optic based Michelson interferometer. Depth scanning is achieved by the longitudinal translation of a reference mirror, and lateral scanning is obtained by the lateral translation of a focused probe beam using scanning mirrors, so that x-z cross sectional images are usually generated. However, this strategy usually sacrifices the lateral resolution of the images[5]. There is also usually the case where *en face* images (x-y) are needed for better comparison with information obtained with other imaging modalities. An example is the studies of the eye, where the scanning laser ophthalmocope (SLO) offers transversal images of the fundus and a large data base of SLO images exist. The SLO expertise in recognizing ailments of the eye could be better transferred to the OCT technology if the images were of the same orientation[6].

Parallel or full-field OCT with ultra-high resolution has been demonstrated recently with a charge-coupled device (CCD) camera using a tungsten halogen lamp[3]. A sensitivity of 90 dB was achieved with 4-s acquisition time. For certain applications, such as the imaging of the human retina, ultra-high acquisition time is needed in order to mitigate the eye motion problem.

In this letter, we present an alternative system in which parallel detection scheme is used to acquire the *en face* images at a given depth in 7 ms. The lateral resolution (1.1 μm) is limited by the optics and the camera pixel size, and the axial resolution (10 μm) is the coherence length of the light source divided by the refractive index of the sample.

We constructed a parallel OCT (POCT) system that was based on a free-space Michelson interferometer design. The schematic of the POCT system is shown in Fig. 1. It consisted of a superluminescent diode (SLD, λ = 679 nm, 10 mW) for illuminating the sample; voice coil and piezo-electric translators (PZTs) for controlling the optical path length of the reference channel; and a scientific-grade 12-bit CCD array for recording two-dimensional interferograms. *En face* slices of the sample object were obtained using a 4-step phase shift reconstruction method[7]. The system was capable of collecting four images in less than 7 ms, each 1 ms in duration followed by a 1-ms delay to allow $\lambda/8$ movement of the piezo-electric mirror, corresponding to a $\pi/2$ phase shift in the interferometer. The reconstructed image of the sample is given by

$$I_{\text{recon}} = \frac{(I_1 - I_3)^2 + (I_2 - I_4)^2}{4(I_1 + I_2 + I_3 + I_4)}, \tag{1}$$

where I_1, I_2, I_3, and I_4 are the four phase-stepped intensity images, respectively.

The axial point spread function for the POCT system is obtained by positioning a planar mirror in the sample channel and sweeping the reference mirror. The axial resolution and the sensitivity of the POCT system are measured to be near 10 μm and 76 dB, respectively.

Figure 2 is the result of validation experiment for the POCT system. Figures 2(a)−(d) show the 4-step raw images of a soiled mirror when the coherence gate was positioned at the mirror surface. The high contrast of the fringes indicates that the reference mirror has reached its specified resting position in the 1 ms prior to the exposure and is not "ringing". Fringe location was measured off-line using separate software to verify the desired $\lambda/8$ steps. Figure 2(e) shows a reconstruction of the soiled mirror using the four interferograms ((a)−(d)). For

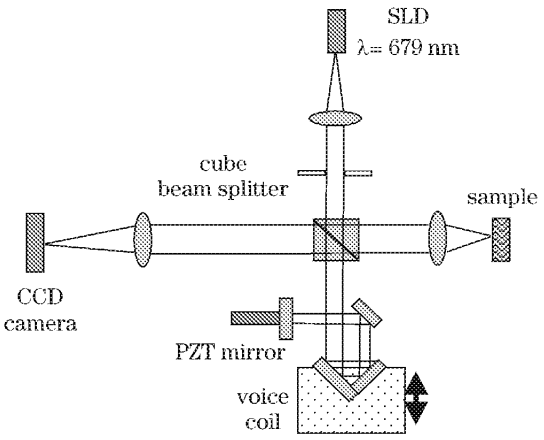

Fig. 1. Schematic diagram of the experimental setup.

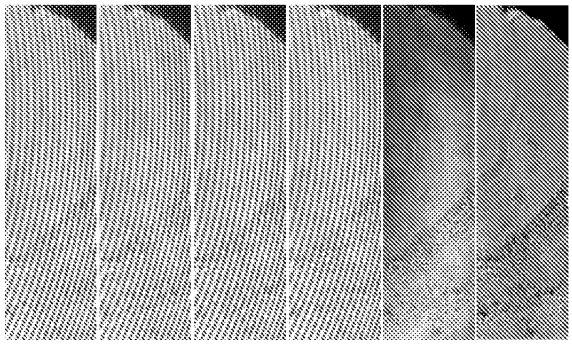

Fig. 2. Validation experiment results of the POCT system. (a)–(d): A temporal sequence of four interferograms collected of a soiled planar mirror inserted in the sample channel of the POCT system. (e): The reconstruction of the soiled planar mirror using the four interferograms shown in images (a)–(d). For comparison, a conventional flood illumination of this same patch of mirror is also shown in image (f).

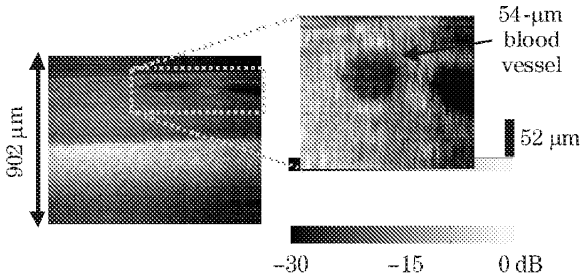

Fig. 3. (Left) Cross-sectional slice (x-z) through a stack of *en face* (x-y) coherence gated reconstructions of an *in vitro* bovine retina. (Right) A subsection of the x-z slice is displayed with the transverse and depth dimensions resized to the same linear scale. The resized image reveals blood vessels (dark patches) that are circular as predicted by histology. Note the relatively sharp edges of the 54-μm diameter blood vessels.

comparison, a conventional flood illumination of the same patch of mirror is shown in Fig. 2(f), realized by blocking the reference channel in the POCT system. Note the strong similarity between the two images, suggesting that the observed structure with coherence gating is not an artifact of the reconstruction. Differences between the two images should be expected as coherence gating reconstruction object information that is confined to the 10-μm coherence length (in tissue) of the light source. Debris on the sample mirror is likely larger than the coherence length.

The POCT setup was also tested for imaging an *in vitro* bovine retina. In the optical system shown in Fig. 1, a section of fresh bovine fundus was placed in the sample channel. A patch of the fundus was flood illuminated and imaged from which coherence gating reconstructions were obtained. A cross-sectional slice (x-z) through the stack of *en face* (x-y) reconstructions of the *in vitro* bovine retina is shown in Fig. 3. The dark region on top is saline solution, which as anticipated reflected little light; the middle gray band is believed to be the retina; the dark elliptical structures lying immediately below the retinal surface are cross sections through small blood vessels; and the bright band deeper in the tissue is suggestive of the highly reflective retinal pigment epithelium layer and choriod. The bright band starts at 365 μm below the retinal surface. As the CCD camera remained focused on the blood vessel for all reconstructions, spatial resolution was poor through much of the image. Yoking the focal plane to the coherence gate will remove this limitation.

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References

1. D. Huang, E. A. Swanson, C. P. Lin, J. S. Schuman, W. G. Stinson, W. Chang, M. R. Hee, T. Flotte, K. Gregory, C. A. Puliafito, and J. G. Fujimoto, Science **254,** 1178 (1991).
2. B. Bouma, G. J. Tearney, S. A. Boppart, M. R. Hee, M. E. Brezinski, and J. G. Fujimoto, Opt. Lett. **20,** 1486 (1995).
3. A. Dubois, L. Vabre, R. Lecaque, and A. C. Boccara, Proc. SPIE **4956,** 14 (2003).
4. M. Ducros, M. Laubscher, B. Karamata, S. Bourquin, T. Lasser, and R. P. Salathé, Opt. Commun. **202,** 29 (2002).
5. E. Beaurepaire, A. C. Boccara, M. Lebec, L. Blanchot, and H. Saint-Jalmes, Opt. Lett. **23,** 244 (1998).
6. A. Gh. Podoleanu, J. A. Rogers, D. A. Jackson, and S. Dunne, Opt. Express **7,** 292 (2000).
7. R. S. Sirohi and F. S. Chau, *Optical Methods of Measurement* (Marcel Dekker, New York, 1999) p. 128.