Spectral calibration in spectral domain optical coherence tomography

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A novel spectral calibration method is developed for spectral domain optical coherence tomography system. The method is based on two measurements of interference spectra from two reference mirror positions. It removes the influence of dispersion mismatch, and hence accurately determines the spectral distribution on the line-scan charge-coupled device (CCD) for sequent precise interpolation. High quality imaging can be realized with this method. Elimination of the degradation effect caused by dispersion mismatch is verified experimentally, and improved two-dimensional (2D) imaging of fresh orange pulp based on the proposed spectral calibration method is demonstrated.

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Spectral domain optical coherence tomography (SD-OCT) is a non-invasive, non-contact imaging modality which can obtain the information of full depth profile by Fourier transform of the acquired spectra within a single exposure, without movement of the reference arm[1−3]. SD-OCT has dramatically improved the dynamic range and imaging rate of OCT techniques[4]. However, the Fourier transform of mutual interference requires uniform sampling in wave number, and the spectrum in spectrometer is evenly spread in wavelength. Therefore, a conversion of the raw spectrographs from λ-space to k-space is essential to avoid deterioration of axial resolution and signal-to-noise ratio (SNR)[5]. An important step in this remapping procedure is spectral calibration, i.e., assigning the correct wavelength to each pixel of the charge-coupled device (CCD) and mapping the index of the pixel array into the corresponding wavelength. In this paper, a novel method of spectrometer calibration is put forward and applied in experiments.

SD-OCT typically consists of a fiber-based Michelson interferometer and a line-scan CCD based spectrometer. If a single reflective surface, such as a mirror, is placed in the sample arm of the interferometer, the detected mutual interference signal between the sample arm and the reference arm at the spectrometer can be expressed as

$$I_{\rm m}(\lambda) = 2a_{\rm r}a_{\rm s}S(\lambda)\cos(2k\Delta z), \tag{1}$$

where $k = 2\pi/\lambda$ is the wave number, $S(\lambda)$ is the spectral density of the light source,$a_{\rm r}$ and $a_{\rm s}$ are the amplitude reflecting coefficients of the reference and sample arm mirrors, respectively, and Δz is the relative optical path difference (OPD) between the two arms.

As mentioned before, spectral calibration is needed to avoid deterioration of axial resolution and SNR. There are several calibration methods proposed to obtain the knowledge of the wavelength incident on the different pixels of the line-scan CCD. One sophisticated calibration method is using a light source that produces several (at least $4-6$) special spectral lines in the wavelength region of SD-OCT spectrometers, then a third-order polynomial fitting can be applied to determine the relationship between pixel number and wavelength. This method is simple and accurate, but an additional calibration source is needed. A parametric iteration method has also been proposed which alters the wavelength assignments until the resulting intensity modulation becomes a perfect sinusoid as a function of k[6]. But the iteration process is of low efficiency. Another calibration method is phase linearization[7]. The phase of the spectral signal can be extracted by using Hilbert transform. If the phase is extracted, then the wavelength distribution is determined. However, when the dispersion mismatch between reference arm and sample arm exists, Eq. (1) can be written as

$$I_{\rm m}(\lambda) = 2a_{\rm r}a_{\rm s}S(\lambda)\cos(2k\Delta z + g(\lambda)), \tag{2}$$

where $g(\lambda)$ represents the dispersion mismatch between two arms. Under this condition, the phase retrieved by Hilbert transform is incorrect because $g(\lambda)$ is wavelength dependent. The complex interference signal after Hilbert transform of Eq. (2) is

$$\tilde{I}_{\rm m}(\lambda) = 2a_{\rm r}a_{\rm s}S(\lambda)\exp[j\phi(\lambda)], \tag{3}$$

where $\phi(\lambda) = \frac{4\pi}{\lambda}\Delta z + g(\lambda)$. If we obtain two interferograms with different OPDs, considering that $g(\lambda)$ is not changed with respect to the OPD Δz, then subtraction of the phases of two different interference signals with different OPDs can remove the influence of dispersion mismatch between two arms. However, there are 2π ambiguities in the Hilbert transform because the solutions of arc-tangent function are limited to a principal value ranging from $-\pi$ to π. From the view point of sampling principle, the maximum phase change between consecutive pixels of CCD is less than π. Thus a simple unwrapping method can be done by adding multiples of $\pm 2\pi$ when absolute jumps between consecutive elements of wrapped phase sequence obtained by Hilbert transform are greater than the default jump tolerance of π. As long as the phase of every pixel on CCD is known, the wavelength distribution is determined.

The spectral calibration method is implemented in our established SD-OCT system shown in Fig. 1. The system is constructed with an 830-nm broadband light source.

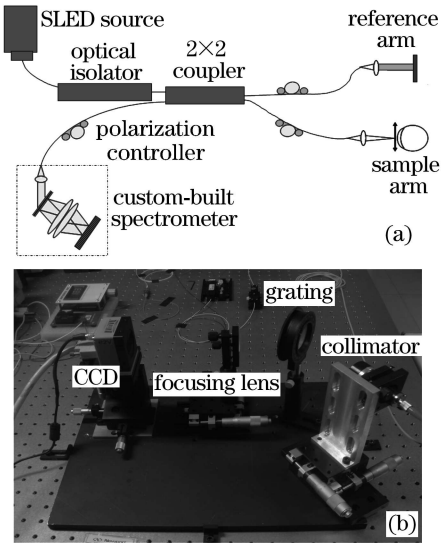

Fig. 1. (a) Schematic diagram of established SD-OCT system and (b) the custom-built spectrometer.

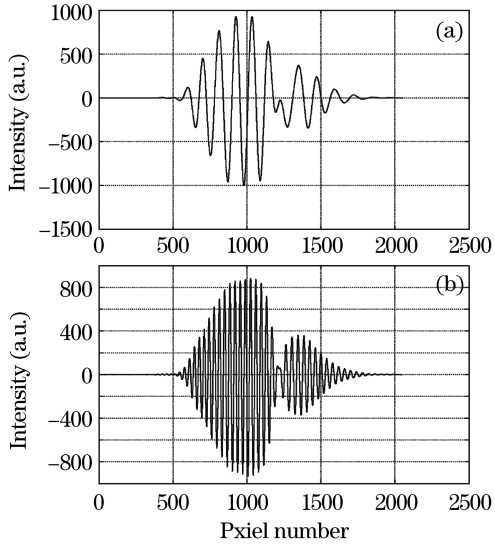

Fig. 2. Interference signals at different OPDs of (a) Δz_1 and (b) Δz_2.

A superluminescent light emitting diodes (SLED, IPSDD0803, Inphenix, USA) emits a beam at the center wavelength of 830 nm with a 3-dB bandwidth of 40 nm, corresponding to a coherence length of 7.6 μm. A polarization-independent fiber isolator is placed immediately after the light source to avoid light reflection back to the light source. Then the beam illuminates a Michelson interferometer where it is split by a 50/50 fiber coupler. Two identical silver mirrors are placed in the reference arm and the sample arm respectively for spectral calibration. Light beams reflecting from reference and sample arms are recombined in the detection arm consisting of a 60-mm focal length achromatic collimating lens, a 1200-line/mm transmission grating under Littrow condition, and a 150-mm focal length achromatic lens. The focused light is projected onto a line-scan CCD camera consisting of 2048 pixels, each 14×14 (μm) in size and 14 b in digital depth. The CCD pitch length resolved spectral resolution is about 0.067 nm which determines the maximum detection depth of 2.56 mm in air. Then spectral data are transferred to the host computer memory from the CCD camera via CameraLink card and a high-speed frame grabber board. In our experiments, the integration time of line-scan CCD is set to be 50 μs, corresponding to the A-scan rate of 20 kHz. Every 100 consecutive spectra data are transferred to the computer and averaged, and then the spectral curve is plotted real-time by a custom-design VC++ program developed for the spectrometer.

In our experiment, we obtained two interferograms with different OPDs Δz_1 and Δz_2 successively. Moreover, $\Delta z_2 - \Delta z_1$ is adjusted to be 0.1 mm via precise translation stage. The two interferograms after subtraction of direct current (DC) terms are illustrated in Fig. 2. We can see that the polarization mode dispersion mismatch between the reference arm and the sample arm exists. Hilbert transform was then applied to obtain the complex signal and the discontinuous phase was unwrapped as mentioned before. Note that we only use the value of central 1024 pixels, corresponding to a spectral range of about 68 nm (1024×0.067 nm).

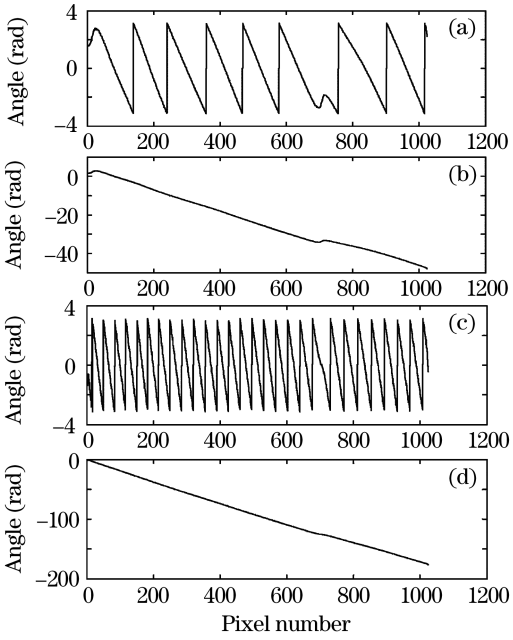

Fig. 3. (a,c) Wrapped phases and (b,d) unwrapped phases corresponding to two optical path length differences.

As illustrated in Fig. 3, the phase of mutual interference term between the sample arm and the reference arm is unwrapped. Then the dispersion term can be cancelled out by subtraction of these two phases. The result is shown in Fig. 4. It can be seen that the dispersion term is almost cancelled out. However, an initial phase must be given to obtain the real phase value. Since the central wavelength is about 830 nm and the spectra range is 68 nm, the wavelength range is from 796 to 864 nm. Considering $\Delta z_2 - \Delta z_1 = 0.1$ mm, so we can set the initial phase to be 2π multiplied by the integral part of 200000/796. Thus the real phase value is obtained by adding the initial phase to the subtraction between the two unwrapped phases of different OPDs. Then the wavelength distribution can be determined by $4\pi\Delta z_{1,2}/\phi(\lambda)$, here $\Delta z_{1,2}$ equals 0.1 mm or 10^5 nm. An enlarged local wavelength

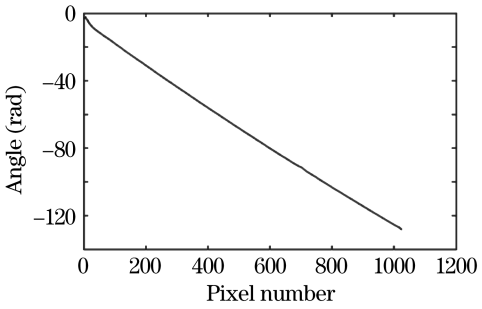

Fig. 4. Subtraction of phase with two different OPDs.

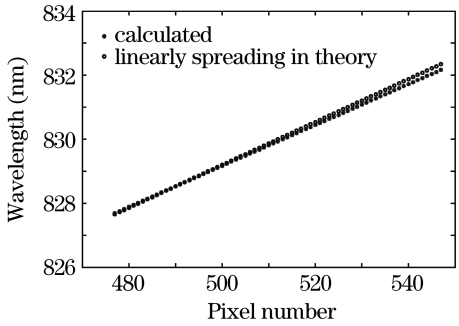

Fig. 5. Wavelength distributions on CCD pixels (central 60 pixels).

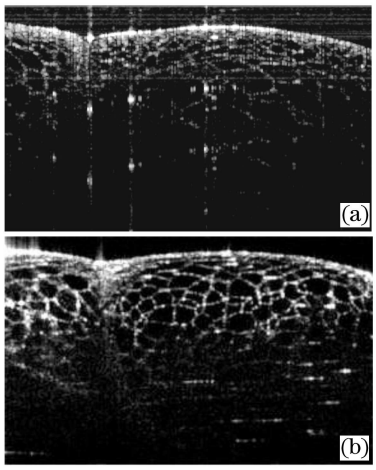

Fig. 6. Images of fresh orange pulp (a) without and (b) with spectral calibration and interpolation.

curve is also shown in Fig. 5. From the results, it can be seen that the practical spacing wavelength between consecutive pixels is no longer constant. And the calculated wavelength range is from 797.32 to 862.1 nm, which is close to the wavelength region (796 − 864 nm) resulting from theoretical linear distribution of spectrometer.

After spectral calibration, an interpolation and sequent Fourier transform are applied. Using this spectral calibration method, two-dimensional (2D) imaging of fresh orange pulp wasperformed. In comparison, the image of fresh orange pulp was also obtained without spectral calibration and interpolation. The lateral scanning was performed by electrical step motor. The image size was about 1.2×1.6 (mm), and the integration time of line-scan CCD was set to be 50 μs, corresponding to the A-scan rate of 20 kHz. The images are shown in Fig. 6. It can be seen that the inner structure of orange pulp is clear after spectral calibration and interpolation, furthermore the deeper structure is also obtained due to the increased SNR.

In summary, we have developed a SD-OCT system at A-scan rate of 20 kHz. A novel spectral calibration method is proposed, which can accurately determine the spectra distribution on the line-scan CCD without the influence of dispersion mismatch. By implementing the method in the established system, elimination of the effect of dispersion mismatch is confirmed and OCT imaging with increased SNR is realized.

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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. G. Häusler and M. W. Lindner, J. Biomed. Opt. **3,** 21 (1998).
3. G. Shi, Y. Dai, L. Wang, Z. Ding, X. Rao, and Y. Zhang, Chin. Opt. Lett. **6,** 424 (2008).
4. P. Bu, X. Wang, and O. Sasaki, Acta Opt. Sin. (in Chinese) **27,** 1470 (2007).
5. R. Leitgeb, C. K. Hitzenberger, and A. F. Fercher, Opt. Express **11,** 899 (2003).
6. B. H. Park, M. C. Pierce, B. Cense, S.-H. Yun, M. Mujat, G. J. Tearney, B. E. Bouma, and J. F. de Boer, Opt. Express **13,** 3931 (2005).
7. R. A. Leitgeb, W. Drexler, A. Unterhuber, B. Hermann, T. Bajraszewski, T. Le, A. Stingl, and A. F. Fercher, Opt. Express **12,** 2156 (2004).