Swept source optical coherence tomography based on non-uniform discrete fourier transform

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A high-speed high-sensitivity swept source optical coherence tomography (SSOCT) system using a high speed swept laser source is developed. Non-uniform discrete fourier transform (NDFT) method is introduced in the SSOCT system for data processing. Frequency calibration method based on a Mach-Zender interferometer (MZI) and conventional data interpolation method is also adopted in the system for comparison. Optical coherence tomography (OCT) images from SSOCT based on the NDFT method, the MZI method, and the interpolation method are illustrated. The axial resolution of the SSOCT based on the NDFT method is comparable to that of the SSOCT system using MZI calibration method and conventional data interpolation method. The SSOCT system based on the NDFT method can achieve higher signal intensity than that of the system based on the MZI calibration method and conventional data interpolation method because of the better utilization of the power of source.

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Optical coherence tomography (OCT)[1] is a noninvasive and noncontact imaging modality that can provide micrometer scale cross sectional images of tissue microstructure[2,3]. Recently, applications of Fourier domain methods to OCT have attracted much attention because of its significant improvements in detection sensitivity and imaging speed[4,5]. A variation of Fourier domain OCT called swept source OCT (SSOCT) measures the backscattered sample information using a laser source whose frequency is rapidly swept with time[6]. Cross sectional images of biology tissue is obtained by Fourier transform of the interference fringe signals.

In order to implement discrete Fourier transform to the discrete sampled data, fast Fourier transform (FFT) algorithm has been widely applied in SSOCT system. One requirement of using FFT is that the sampled data must be equally spaced in the frequency domain (k-space), otherwise, image quality in terms of resolution, sensitivity, and absolute measures would be degraded. However, directly sampled raw data in a SSOCT system is not equally spaced in k-space because of frequency nonlinearity verse time of its swept laser source.

In order to reach the best image quality, calibrating the raw data from non-uniformly spaced one to equally spaced one in k-space is necessary. In recent literatures, several approaches for frequency calibration for SSOCT have been demonstrated. One of them is the simultaneous frequency monitoring method using a fiber Fabry-Perot (FFP) interferometer[7] to calibrate the interference data, in which a portion of the light source is introduced into the FFP to generate series of peak signals. Via simultaneously detecting and storing the OCT interference signal and FFP signal, calibration parameters can be calculated using the output signal of FFP, and then the linearly frequency spaced data can be acquired using the calibration parameters. This method requires a high-end analog/digital (A/D) converter and large memory space to store the two signals. The frequency even clock method[8] is similar to the simultaneous frequency monitoring method, but the output from an FFP or a fiber Bragg grating (FBG) is monitored by a photo detector and converted to a transistor-transistor logic (TTL) pulse train, which is used as a sampling clock signal of an A/D converter which detects the interference signal. This method does not store the FFP/FBG output in the memory, but still requires expensive FFP/FBG. Data interpolation method is a conventional software method to calibrate the interference spectrum signal. The method does not need FFP/FBG, and in this method, the detector signal is sampled in constant time intervals and nonlinearly in k-space, and then the interference signal is interpolated to get data equally spaced in k-space[9]. Huber *et al.* demonstrated a fast calibration and rescaling algorithm by using a FFP and a nearest neighbor check algorithm[10]. This method is capable of high-speed calibration because of the elaborated algorithm, but a FFP device is still required.

As mentioned above, the hardware calibration methods based on FFP/FBG require expensive FFP/FBG and additional storing space, and the software calibration method has a drawback of interpolation inaccuracy. Therefore in this letter, we introduce a non-uniform discrete fourier transform (NDFT) method and apply it process raw data of OCT interference signal without any additional expensive calibration device.

Firstly we briefly review the definition of Fourier transform in the continuous domain and discrete domain. The Fourier transform of a time signal $f(t)$ in the continuous domain is defined by

$$F(\omega) = \int_{-\infty}^{+\infty} f(t)\mathrm{e}^{-\mathrm{j}\omega t}\mathrm{d}t, \quad (1)$$

where $\omega = 2\pi f$ and f is the temporal frequency. The extension of Eq. (1) to the discrete domain is called discrete

Fourier transform (DFT), which is given by

$$F(m)=\sum_{n=0}^{N-1} f(t_n)\mathrm{e}^{-\mathrm{j}\frac{2\pi}{N}mn}, \tag{2}$$

where $m = 0, 1, \ldots, N-1$ and $\{f(t_n)\}$ is N samples of the signal $f(t)$ taken at regular intervals.

Now we generalize the definition of the Fourier transform from the regular sampling to the irregular sampling. The definition of the non-uniform discrete fourier transform (NDFT) is given by[11]

$$F(m)=\sum_{n=0}^{N-1} f(t_n)\mathrm{e}^{-\mathrm{j}m\frac{2\pi}{T}t_n}, \tag{3}$$

where $m = 0, 1 \ldots, N-1,$ T is the range of the extension for the samples, and t_n is temporal coordinate of the arbitrary signal sample points, with $t \in [0, T]$. Consider the differences between the definition of DFT and NDFT, firstly, the samples in the frequency are taken at intervals $2\pi/T$ in the irregular case instead of $2\pi/N$ in the regular case; secondly, the irregular sampling coordinate t_n appears in the exponent instead of the integer index n in the regular case.

In the practical SSOCT case, the Fourier transform from interference spectrum signal to sample depth information is given by

$$i(k)=\ S(k)\sum_i 2a_i\cos(2kz_i+\phi(z_i)) \xrightarrow{\mathrm{FT}} I(z)=\sum_i a_i\Gamma(z-z_i)+\sum_i a_i\Gamma(z+z_i), \tag{4}$$

where $S(k)$ is the power spectrum of the swept source, a_i and z_i are reflectance and position of scatters within the sample, $\phi(z_i)$ represents the phase of the reflectance profile of the sample, and $\Gamma(z)$ represents the envelope of the coherence function of the source. In Eq. (4), wave number of the swept source and imaging depth is a pair of Fourier transform. Due to the nonlinear relationship between the wave number and time of the swept source output and linear data acquisition with time, the wave number of the sampled interference spectrum signal is unequally spaced distributed. In this case, the samples are taken irregularly in the wave number domain (k-space) but regularly taken in the depth domain (z-domain). That is to say the regularly taken samples $I(z)$ in z-domain have a fixed interval Δz given by

$$\Delta z=\frac{2\pi}{K}, \tag{5}$$

where K is the wave number range of the sampled interference spectrum signal. The expression of the non-uniform discrete fourier transform in the practical SSOCT data processing is

$$I(z_m)=\sum_{n=0}^{N-1} i(k_n)\mathrm{e}^{-\mathrm{j}\frac{2\pi}{K}k_n z_m},\ m=0,1,\cdots N-1, \tag{6}$$

where z_m is the depth coordinate, $i(k_n)$ is the sampled interference spectrum signal, k_n is the wave number of the sampled interference spectrum signal. Equation (6) can be written in matrix form as

$$I=Di, \tag{7}$$

where

$$I=\begin{bmatrix} I(z_0)\\ I(z_1)\\ \vdots\\ I(z_{N-1})\end{bmatrix}, \tag{8}$$

$$i=\begin{bmatrix} i(k_0)\\ i(k_1)\\ \vdots\\ i(k_{N-1})\end{bmatrix}, \tag{9}$$

$$D=\begin{bmatrix} 1 & 1 & \cdots & 1\\ p_0^{-1} & p_1^{-1} & \cdots & p_{N-1}^{-1}\\ p_0^{-2} & p_1^{-2} & \cdots & p_{N-1}^{-2}\\ \vdots & \vdots & \ddots & \vdots\\ p_0^{-(N-1)} & p_1^{-(N-1)} & \cdots & p_{N-1}^{-(N-1)}\end{bmatrix}, \tag{10}$$

and p_n is expressed by

$$p_n=\exp(\mathrm{j}\frac{2\pi}{K}k_n),\quad n=0,1,\cdots N-1. \tag{11}$$

The matrix D has a special form called Vander Monde matrix and fully determined by N points. The determinant of D is given by

$$\det(D)=\prod_{i\neq j,i>j}(p_i^{-1}-p_j^{-1}). \tag{12}$$

Hence, D is nonsingular for any N distinct sampling points, and the NDFT uniquely exists[12].

According to Eq. (6), the accuracy of NDFT depends largely on the accuracy of the wave number of the sampled interference signal k_n, which can be achieved according to the relationship between the wave number and time. The output of the swept source must be calibrated accurately. According to the wave number function and sampling rate, we get the series of accurate k_n and the wave number range K of the swept source.

For comparison with the NDFT method, we also introduce another two data processing methods. One is a frequency calibration method applied to the SSOCT system by adding an additional device, a Mach-Zender interferometer (MZI), and the nearest neighbor check algorithm[10]. The other one is a conventional data interpolation method.

The SSOCT experimental setup is shown in Fig. 1. The output of the light source (HSL2000, Santec Inc.) passes through the 50/50 fiber couplers 2 and 3 into the reference arm and sample arm, respectively. The sample arm is constituted by a fiber collimator, an achromatic lens of 40-mm focal length, and an electrical motorized translation stage. Backscattered light from the sample returns to the fiber coupler 3. The reference arm has a polarization controller, a fiber collimator, a focusing lens, and a plane mirror (RM). A balance detector (BPD) detects interference light signals and converts them into voltage signals. One analog input channel of the data acquisition card (National Instruments, model NI5122) digitizes the voltage signal. Then the sampled data representing one OCT image is transferred to the computer memory. After data processing and image reconstruction, we get tomographic image of biological tissue samples.

When we use the MZI to calibrate the interference spectrum signal in real time, as shown in Fig. 1. Within the dashed-line box, a part of the output is introduced through fiber coupler 1 (10/90) to the MZI. The MZI signal is sampled by the second input channel of the DAQ card synchronously at a 100-MS/s sampling rate. By using the nearest neighbor check algorithm[10], N equidistant sample points are obtained. OCT image could be reconstructed by these calibrated data through FFT algorithm.

When we use the NDFT method, the whole original sample points are firstly stored in the hard disk of personal computer (PC). Then these data are processed using NDFT by a MATLAB program.

From the test report of the light source, the wave number function $k(t)$ can be a prior known parameter fitted by a cubic polynomial as

$$k(t) = at^3 + bt^2 + ct + d. \quad (13)$$

The result of curve fitting and the value of the fitted coefficients a, b, c, and d are shown in Fig. 2. The result demonstrates that the cubic polynomial fitting matches well with the experimental wave number data of the swept source.

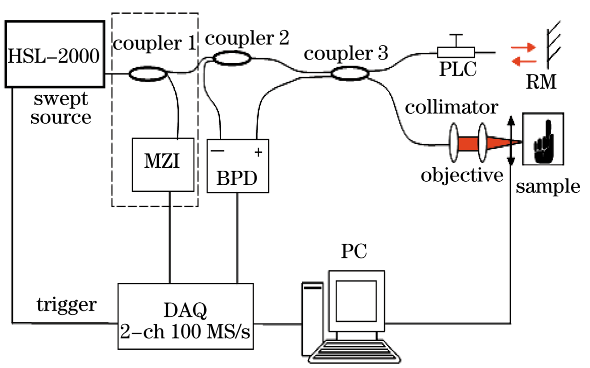

Fig. 1. SSOCT system setup using NDFT algorithm and MZI calibration method (with and without the frame of the dashed line, respectively).

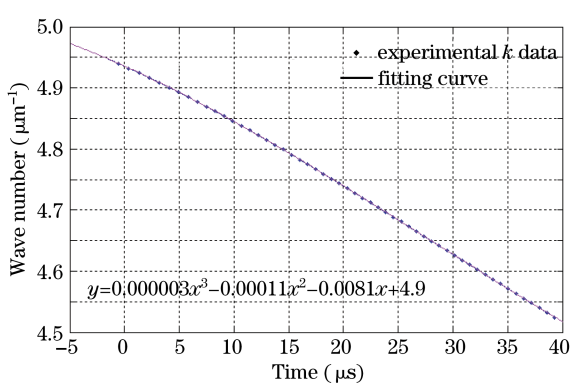

Fig. 2. Curve fitting result of wave number function of the swept source.

To determine the axial resolution of the SSOCT system based on the NDFT method, we investigated the axial point spread function (PSF) by measuring the A-line profile of a partially reflecting mirror sample (95% reflectivity). A representative of a PSF at the depth of 510 μm from the zero-delay point is depicted in Fig. 3. From the graph, we can recognize that the resolution achieves 8.3 μm, while theoretical resolution with Gaussian spectrum is 7.2 μm based on the 107-nm bandwidth of the swept source.

To compare the axial resolution of SSOCT system using NDFT method, MZI calibration method, and data interpolation method, we measure the PSF of the SSOCT system with a mirror sample at the depth of 318 μm, using the three methods, respectively. Wherein, the data interpolation uses a conventional cubic spline to interpolate the raw sample data.

The axial resolution results are shown in Fig. 4 and Table 1. The resolution using NDFT method is 8.1 μm, and is comparable with that of using MZI calibration method. The axial resolution using conventional data interpolation method is 9.5 μm, and is a bit lower than that of using NDFT method. Moreover, the signal intensity of the SSOCT system using NDFT method is higher than that of using MZI calibration method and data interpolation method because of better utilization of the power of the source. The sensitivity of the SSOCT system with NDFT method can reach 113 dB approximately.

To compare the feasibility of the NDFT method with that of MZI calibration method and data interpolation method in biological imaging, we obtaine images of a shrimp in vivo. Figure 5(a) is the picture of the sample under imaging. The black line in the picture marks the lateral scanning direction and position. The OCT image of the neck area of the shrimp sample based on NDFT method, MZI calibration method, and data interpolation method are shown in Fig. 5(b), (c), and (d) for comparison, respectively.

Table 1. Axial Resolution Comparison Results Using Four Different Methods

Method	NDFT	MZI	Data Interpolation	Direct FFT
Axial Resolution (μm)	8.1	8.1	9.5	23.3
Intensity (a.u.)	1	0.8	0.9	0.6

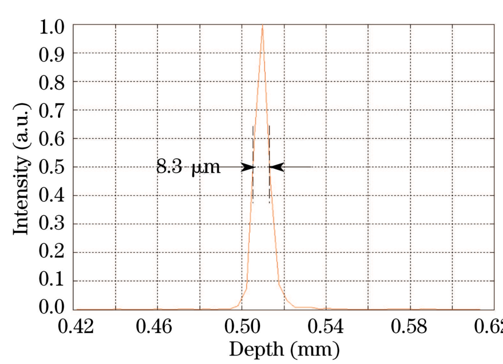

Fig. 3. Representative of PSF at depth of 510 μm.

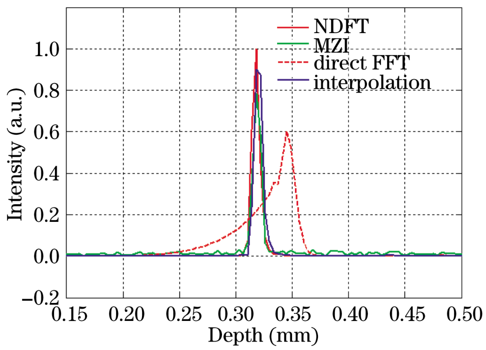

Fig. 4. PSF measured using different methods.

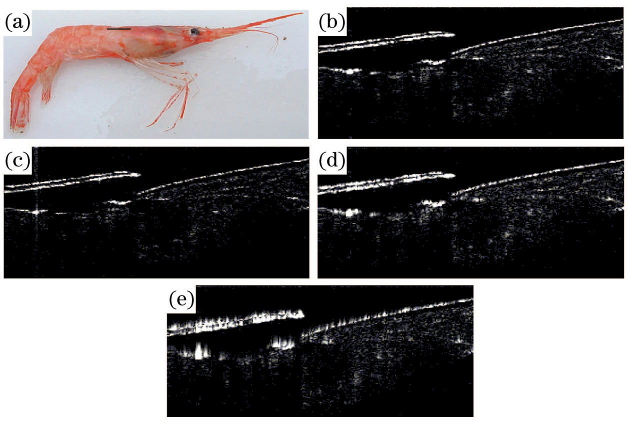

Fig. 5. (a) Shrimp under imaging, (b) OCT image of neck of shrimp based on NDFT method, (c) MZI calibration method, (d) conventional data interpolation method, (e) direct FFT from sampled raw data.

From the images above, we can confirm that the image from NDFT method (Fig. 5(b)) has the comparable resolution with that of the MZI calibration method (Fig. 5(c)). And the resolution of the NDFT image is a bit higher than that of the image from data interpolation method because of interpolation error. Figure 5(b) displays more detailed information at larger depth position than that of Fig. 5(c) because of higher sensitivity.

For the case of uniform DFT used in MZI calibration and interpolation methods, the well established FFT could be used; in contrast, the computational complexity of the NDFT method is $O(n\log^2 n)$[13]. Therefore, in the shrimp images construction, the computation time of the CPU in NDFT method is about four times compared with the uniform DFT method. However, the higher performance of PC and a more elaborated NDFT algorithm could make up for the overall computational complexity.

In summary, NDFT method is introduced and implemented in our SSOCT system for image reconstruction. Using the method, high sensitivity and high resolution images have been obtained. The swept source OCT based on NDFT has an axial resolution of 8.1 μm. The axial resolution is comparable with that of the SSOCT system using MZI calibration method and conventional data interpolation method. Based on the NDFT method, SSOCT system achieves a higher signal intensity because of better utilization of swept source power. The SSOCT system based on the NDFT method does not need additional calibration device. In comparison with MZI calibration method, NDFT method brings cost reduction and simplified system configuration. A modified NDFT method based on weighted non-uniform Fourier transform is under investigation.

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