Abstract
We present a method of parallel full range complex Fourier-domain optical coherence tomography (FDOCT) that is capable of acquiring an artifacts-free two-dimensional (2-D) cross-sectional image, i.e. a full range B-scan tomogram, by a single shot of 2-D CCD camera. This method is based on a spatial carrier technique, in which the spatial carrier-frequency is instantaneously introduced into the 2-D spectral interferogram registered in parallel FDOCT by using a grating-generated reference beam. The spatial-carrier-contained 2-D spectral interferogram is processed through Fourier transformation to obtain a complex 2-D spectral interferogram. From the 2-D complex spectral interferogram, a full range B-scan tomogram is reconstructed. The principle of our method is confirmed by imaging an onion sample.

Key words: optical coherence tomography, Fourier domain detection, spatial carrier frequency.

1. Introduction
Fourier-domain optical coherence tomography (FDOCT) [1, 2] has been demonstrated to hold more clinical applicability than conventional Time domain OCT (TDOCT), benefiting from its advantages of high acquisition speed and sensitivity [3]. However, FDOCT suffers from the so-called complex conjugate, dc and autocorrelation artifacts, of which the first reduces the imaging depth range by half, and the last two limit the signal to noise ratio. These disturbing artifacts are due to the straightforward Fourier transformation of the detected real-valued spectral interferogram. To eliminate these artifacts, various methods to reconstruct the complex spectral interferogram have been proposed over the last few years. First, a technique based on phase-shifting interferometry was used [4], where the complex spectral interferogram was retrieved from multiple phase-shifted spectral interferograms. However, several interferograms are required to be measured sequentially for reconstructing a full range axial line image (A-scan), resulting in longer measurement time. In addition, definite phase step between phase-shifted interferograms require a high stability of the optical system and the sample, which precludes its application to in vivo measurement. To improve this method, simultaneous detection of multiple phase-shifted interferograms using $3 \times 3$ fiber couplers [5], polarization-based optical components [6], and recently dual-reference detection [7] were proposed, but the system's complexity and cost are considerably increased.

Alternatively, carrier-frequency technique is another method to reconstruct the complex interferogram [8]. Recently, carrier-frequency-based methods [9, 10, and 11] have been employed to realize real-time full range complex FDOCT. In these methods the reference beam was phase modulated during lateral scanning of the probing beam to introduce a spatial carrier-frequency into the two-dimensional (2-D) spectral interferogram, from which the complex interferogram can
be obtained by Fourier transform or Hilbert transform processing. These methods require only one measurement to acquire a full range FDOCT A-scan image, but the spatial carrier frequency was generated by time-dependent phase modulation, thus any phase error during the sequential phase modulation due to the motion of the measured sample may degrade the suppression ratio of the complex conjugate artifact, especially in Doppler imaging [12, 13]. Therefore a spatial carrier technique, where a spatial carrier frequency is generated by spatially dependent phase modulation at an instant of time, is more suitable for time-varying objects measurement [14].

We have previously reported a one-shot parallel complex full range FDOCT [15] by combining a spatial carrier technique with parallel FDOCT [16], where a tilted reference mirror was used to generate a spatial carrier-frequency into the 2-D spectral interferogram registered in parallel FDOCT. Although the use of tilted reference mirror as a linear spatial phase modulator is simple, the lateral imaging range is limited. An alternative approach to generate linear spatial phase modulation is to use a reflective grating. This grating-based method was previously used as a reference delay line to achieve a scan-free coherence microscopy [17], which was later extended to a high-speed TDOCT [18]. Here, for the first time, we use a grating-generated reference beam to introduce instantaneously a spatial carrier-frequency into the 2-D spectral interferogram registered in parallel FDOCT, to implement a single-shot parallel full range complex FDOCT. The 2-D complex spectral interferogram is reconstructed through Fourier transformation from the spatial-carrier-contained 2-D spectral interferogram with a single shot of the 2-D CCD camera. From the 2-D complex spectral interferogram, a full range B-scan tomogram is obtained. Therefore our method is more insensitive to the sample motion-induced phase error than the other proposed carrier-frequency methods.

2. Method
The schematic diagram of the proposed single-shot parallel full range complex FDOCT system is shown in Fig.1. This system is similar to that described previously in Ref. [15] except that a reflective grating is used as a reference instead of a tilted mirror. In brief, a parallel FDOCT system was adopted to record a 2-D spectral interferogram with a single shot of 2-D CCD camera. The reflective grating G1 was positioned with the Littrow configuration in the reference arm of the interferometer to introduce a spatial carrier-frequency into the 2-D spectral interferogram instantaneously. We define a coordinate system with the z axis along the direction of propagation of light, the x axis the spectral direction, and y axis the lateral direction.
Fig. 1. The schematic diagram of the single-shot parallel full-range complex FDOCT
SLD, super-luminescent diode; L1, the collimator objective lens; L2, L3, L4, L5, L6 denote lenses of focal length 100, 100, 100, 40, 100 mm, respectively; CL, cylindrical lens of focal length 200 mm; BS, cube beamsplitter; G1, G2 denote grating with 600, 1800 lines/mm, respectively. The grating G1 is positioned with Littrow configuration in y-z plane, which is not denoted in the figure.

The grating G1 installed with Littrow configuration was performed in y-z plane, resulting in a tilted reference wavefront. The Littrow angle $\theta$ is determined by

$$\theta = \sin^{-1}(m\lambda_0 / 2p),$$  \hspace{1cm} (1)

where $\lambda_0$ is the center wavelength of light, $p$ is the grating period, and $m$ is the diffraction order. When the first-order diffracted light is selected, a spatial carrier frequency $f_0$ is introduced into the 2D spectral interferogram in the lateral direction, which is given by

$$f_0 = 2tg\theta / \lambda,$$ \hspace{1cm} (2)

where $\lambda$ is the wavelength of light. So the spatial-carrier-contained 2-D spectral interferogram can be expressed as

$$g(k, y) = g_0(k, y) + 2\sum_n S(k)\sqrt{\alpha_n(y)\beta_n} \cos\left[2k\left(z_n(y) + y \cdot tg\theta\right)\right]$$ \hspace{1cm} (3)

where $k = 2\pi / \lambda$ is the wave number; $y$ is the lateral position; $g_0(k, y)$ includes the dc and autocorrelation terms; $S(k)$ is the spectrum of the light source; $\alpha_n(y)$ is the reflectivity of the $n$’th interface within the sample with respect to lateral position $y$; $\beta_n$ is the first-order diffracted efficiency of the grating G1; $z_n(y)$ is the one-pass optical path difference between the probing beam reflected by the $n$’th interface within the sample and the reference beam with respect to lateral position $y$. Equation (3) can be rewritten as
\[ g(k, y) = g_n(k, y) + \sum_n b_n(k, y) \exp(i2\pi f_0 y) + \sum_n b_n^*(k, y) \exp(-i2\pi f_0 y), \]  \hspace{1cm} (4)

where \( b_n(k, y) = S(k) \sqrt{\alpha_n(y)\beta_n} \exp[i2kz_n(y)] \) and \(*\) denotes the complex conjugate operator. Fourier transformation of interferogram \( g(k, y) \) with respect to lateral position \( y \) for each \( k \) yield

\[ G(k, f_y) = G_n(k, f_y) + \sum_n B_n(k, f_y - f_0) + \sum_n B_n^*(k, f_y + f_0), \]  \hspace{1cm} (5)

where \( G \) and \( B \) are the Fourier transformation of \( g \) and \( b \), respectively; \( f_y \) is the spatial frequency along \( y \) direction. When the spatial carrier frequency \( f_0 \) is large enough, the three spectra on the right-hand side of equation (5) can be separated from each other. Then by band-pass selecting the spectrum of \( \sum_n B_n(k, f_y) \) in positive frequency region and inverse Fourier transforming to the original spatial domain, we can obtain the complex 2-D spectral interferogram

\[ g_{\text{comp}}(y, k) = \sum_n h_n(k, y) = \sum_n S(k) \sqrt{\alpha_n(y)\beta_n} \exp[i2kz_n(y)]. \]  \hspace{1cm} (6)

Above-mentioned Fourier transform processing is indeed the same as the Hilbert transform method used by Ref.[11]. Finally, taking inverse Fourier transformation of the complex 2D spectral interferogram with respect to \( k \) for each \( y \), a complex function

\[ \hat{I}(y, z) = \sum_n \sqrt{\alpha_n(y)\beta_n} \Gamma(z - 2z_n(y)) \]  

is obtained, where \( \Gamma \) is the first-order electric field correlation function. Taking the amplitude of \( \hat{I}(y, z) \), we can obtain the full range B-scan tomogram.

3. Results and Discussions

The experimental setup shown in Fig. 1 was constructed. A super-luminescent diode (SLD) with a central wavelength \( \lambda_0 \) of 840 nm and a FWHM bandwidth of 50 nm was used as a light source.

The home-built spectrometer consisted of a reflective grating (G2, 1800 lines/mm), a lens L6 with focal length of 100 mm, and a 2-D CCD camera (Sony XCHR-50, 9-bit, 648×494 pixels, 60 frames per second).

We measured a biological sample. Figure 2(a) shows the cross-sectional image of an onion sample with our proposed method, where the complex conjugate, dc and autocorrelation artifacts are eliminated, compared with the image obtained by a straightforward FDOCT as shown in Fig. 2(b). The suppression ratio of the complex conjugate artifacts was measured to be 28dB. The lateral measurement range was \( \sim 1 \) mm determined by the linear imaging range of CCD camera. The available full depth range in air was \( \sim 1.8 \) mm determined by the spectrometer resolution. The full range B-scan rate of our method is determined by the frame rate of CCD camera (60Hz), which suggests a real-time full range FDOCT B-scan imaging is possible.
Fig. 2. Cross-sectional image of onion sample obtained by (a) single-shot parallel full range complex FDOCT and (b) straightforward FDOCT.

The system sensitivity was measured to be 78 dB with a partial reflector as a sample. A sensitivity roll off with respect to depth (z axis) was observed. This fall-off of sensitivity was primarily due to the limited resolution of the home-built CCD spectrometer. The numerical error of the wavelength to wavenumber rescaling could also strengthen the fall-off. In our experiment, this fall-off of sensitivity also appeared along the lateral direction. This degradation may be due to the Gaussian intensity profile of the line illumination and vignetting effect of the CCD. In addition, because an SLD is a spatially coherent light source, coherent crosstalk among the lateral points may cause additional degradation of the sensitivity. This coherent crosstalk can be suppressed by using spatially incoherent light source.

The imaging resolution of our system is different for each axis. Along the x axis, the resolution is defined as the focal spot size of the probe beam, and theoretically estimated as 33.6 μm, which in practice was degraded by the lateral coherent crosstalk effect. The resolution in y axis was 3.0 μm depending on the pixel size of the CCD camera. The depth resolution was 6 μm in air determined by the coherence length of SLD.

4. Conclusion
In summary, we have demonstrated a single-shot parallel complex FD-OCT by using a grating-generated spatial carrier-frequency. The method is insensitive to the phase error due to the motion of the measured object. With this method, a parallel full range complex FDOCT system can be used for high sensitivity B-scan-based Doppler imaging because it is free of motion artifacts while maintaining relatively a long integration time compared to scanning FD-OCT system.

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