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Depth extension and sidelobe suppression in optical coherence tomography using pupil filters

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Abstract: We demonstrate a new focus engineering scheme to achieve both extended depth of focus (DOF) and sidelobe suppression in spectral-domain optical coherence tomography (SD-OCT) system. Each of the illumination pupil function and the detection pupil function is modulated using an annular pupil filter implemented by center obscuration. The two pupil filters are arranged in a dark-field configuration such that the first sidelobe of the illumination point-spread function (PSF) matches the first minimum of the detection PSF in the lateral focal plane. We tested the feasibility of the proposed scheme numerically, and then constructed a dark-field OCT (DF-OCT) system to further verify its effectiveness experimentally. Simulation results show that a DOF gain of 4.2 can be achieved compared with a full aperture OCT (FA-OCT) system, with a suppression ratio of 2.9 dB for the first sidelobe compared with an annular-aperture bright-field OCT (BF-OCT) system. Experimental results show that the constructed DF-OCT extends the DOF by three-fold compared with the constructed FA-OCT, and suppresses the first sidelobe by 3.1 dB compared with the BF-OCT. The penalty for the extended DOF is an ~11.6 dB drop in sensitivity compared with the FA-OCT system.

OCIS codes: (110.4500) Optical Coherence Tomography; (170.4500) Optical coherence tomography; (170.3880) Medical and biological imaging; (120.3890) Medical optics instrumentation.

References and links
1. Introduction

Optical Coherence Tomography (OCT) is a powerful non-invasive imaging technique based on low coherence interferometry [1-3]. Through measuring the magnitude and echo time delay of the backscattered light, OCT is able to provide cross-sectional images of microstructures of biological tissues. It has received extensive research interests in the past two decades, and now has become a well-established routine clinical diagnostic tool for the detection of eye and skin diseases.

Lateral resolution of an OCT system is decided by the diffraction limited spot size of the focused beam. It is typically defined as the 1/e²-intensity beam waist radius in the focal distance. Although a smaller spot size, and thereby finer lateral resolution, could be achieved by using focusing system with larger numerical aperture (NA), the depth of focus (DOF) [4] is compromised due to the trade-off between the lateral resolution and the DOF of a confocal system. To achieve a high lateral resolution along with an extended DOF, various approaches have been proposed [5-23].

Taking phase information into account, a class of methods featured with digital refocusing, including inverse scattering approach [5-8] and two-dimensional scalar diffraction model based digital refocusing [9], have been demonstrated. They could achieve spatially invariant resolution equivalent to what is achieved at the focal plane throughout the entire illuminated...
volume. These methods are elegant since there is no penalty for the sensitivity and negligible modification to the hardware system. However, phase stability during a volumetric scan is required to reconstruct images, which could be challenging for \textit{in vivo} imaging. Another method, namely, depth-encoded synthetic aperture based refocusing [10], is phase stable and very promising if the number of zones could be scaled up without significant penalty in signal loss.

Unlike the digital refocusing methods, focus engineering methods, including axicon optics [11-17] and phase/amplitude apodization [18-25] methods, physically reduce the spot size and/or extend the focal range, but with sacrifice of signal losses and sidelobe artifacts. Bessel beam generation using axicon lens is a typical method to extend DOF [17], and various OCT systems using axicon optics have been reported [12-16]. It has been demonstrated that an axicon based OCT system is associated with a signal loss of ~13 dB at the peak for both illumination and detection beams [15]. Recent results show that optical efficiency of such an axicon based system is solely dependent on the Fresnel number [17]. By separating Bessel-beam illumination and Gaussian-field detection, Leitgeb \textit{et al} improved the power efficiency of an axicon based system and suppressed the sidelobes, especially for the second and higher order sidelobes [12]. Extending DOF using phase [18-20] or amplitude [21-24] apodization techniques are attractive because the fabrication and miniaturization are relatively easy. A new low Fresnel number graded-index (GRIN) fiber based phase mask structure, which achieves a DOF gain of 2 with 5 dB sensitivity reduction, is presented for ultrathin fiber probes [19]. OCT systems incorporated with an annular aperture have been utilized for cellular and subcellular imaging in various organ systems [23-25].

However, the above mentioned focus engineering methods are associated with a significant sidelobe issue. Such sidelobes, if not managed appropriately, introduce artifacts to OCT images and degrade the effective resolution of the OCT system. In this paper, we propose a new focus engineering scheme which is capable of extending DOF and suppressing the most prominent first sidelobe at the same time. In our method, the illumination and detection pupil functions are modulated using annular amplitude pupil filters arranged in a dark field configuration. With appropriate radii chosen for both illumination and detection pupil filters, the first sidelobe of the illumination PSF collocates with the first minimum of the detection PSF, therefore, such a simple configuration effectively reduces the magnitude of the first sidelobe.

2. Principle of proposed OCT system

2.1 Theory

A simplified SD-OCT setup with two center-obscured apertures that are respectively adopted in the illumination and detection arms is shown in Fig. 1(a). The two apertures are of general type and can be implemented with either amplitude-apodization or phase-apodization methods. The shapes of the two apertures as well as the coordinates and notations around the sample and focal planes are shown in Figs. 1(b) and 1(c).

Without loss of generality, we assume that both apertures used in this paper are realized with the simple amplitude-apodization method. To obtain an extended illumination focus, the aperture 1 is utilized to generate a quasi-Bessel illumination beam. The function $p_1(k, r)$ of aperture 1 can be expressed as,

$$p_1(k, r) = \begin{cases} 
1 & r_o > r_1 \\
0 & \text{otherwise} 
\end{cases}$$

(1)

The process of a collimated illumination beam (with radius $a_o$) passing through aperture 1 and being focused onto the sample is shown in Fig. 1(b). Assume a collimated input beam and an infinity-corrected objective lens, the normalized wavelength dependent field amplitude distribution around the focal region can be expressed as [26, 27],
Fig. 1. (a) Schematic of a typical SD-OCT system with aperture 1 adopted in the illumination path while aperture 2 in the detection; (b) a collimated illumination beam passes through the designated amplitude modulating aperture 1 and is focused by an infinity-corrected objective lens onto the sample; (c) a detection light beam passes through the designated amplitude modulating aperture 2.

\[
g_{\rho\omega}(k, \rho, u) = 2\sqrt{S(k)} \int_0^1 \tilde{f}(k, r) \rho_1(k, r) J_0(\rho r) \exp[-\frac{1}{2} iur^2] dr
\]

\[
= 2\sqrt{S(k)} \int_0^1 \tilde{f}(k, r) J_0(\rho r) \exp[-\frac{1}{2} iur^2] d \rho
\]

(2)

where \( k = 2\pi / \lambda \) is the wave number and \( \lambda \) is the wavelength of light source; \( 0 < r < 1 \) is the radial coordinate of objective lens’s pupil plane normalized by the radius \( a_0 \) of aperture 1 as shown in Fig. 1(b); \( \rho \) and \( u \) denote the simplified radial and axial coordinates in the sample space respectively, and are expressed as

\[
\rho = k(\text{NA}) R,
\]

\[
u = k(\text{NA})^2 Z,
\]

(3)

with \( R \) and \( Z \) being the real radial and axial coordinates in the sample space, \( \text{NA} \) is the effective numerical aperture of the objective lens. \( S(k) \) is the spectral intensity distribution of the light source; \( J_0 \) is a Bessel function of the first kind and order zero; \( \tilde{f}(k, r) \) is the amplitude profile of the fiber mode in the pupil plane.

Under the condition of Gaussian approximation for circular, linear-polarized input light beam, the field distribution \( \tilde{f}(k, r) \) on the pupil plane can be expressed as

\[
\tilde{f}(k, r) = 2\pi \left[ r_0(k) \right]^2 \exp \left\{ -\frac{1}{2} \left[ \frac{2\pi r_0(k) a_0}{f_0 \lambda} \right]^2 \right\}
\]

(5)

where \( f_0 \) is the focal length of the objective lens with \( a_0 / f_0 = \sin(\text{tan}^{-1}\text{NA}) \); \( \lambda \) is the center wavelength of the light source; \( r_0 \) is the obscuration radius of the aperture 1. \( r_0(k) \) is the wavelength dependent mode field radius. Under Gaussian approximation, such mode field radius can be expressed as [28],

\[
r_0(k) = \frac{r_{oc}}{\sqrt{2 \ln V(k)}}
\]

(6)

where \( V(k) = k r_{oc} \text{NA}_f \) is the fiber parameter with \( \text{NA}_f \) being the effective fiber numerical aperture; \( r_{oc} = 2.5 \mu m \) is the core radius of the single mode fiber.

After passing through the aperture 1, the illumination beam is no longer Gaussian-shaped, which thus introduces sidelobes to PSF of the sample arm optics. To suppress such sidelobes,
another amplitude-apodization based aperture 2 (Fig. 1(c)) is designed. With a radius of \( r_2 \) and an obscured center radius of \( r_3 \), this pupil filter \( p_2(k, r_2, r_3) \) can be expressed as,

\[
p_2(k, r_2, r_3) = \begin{cases} 
1 & r_2 < r_u < r_3 \\
0 & \text{otherwise}
\end{cases}
\]  

(7)

With Gaussian approximation of circular, linear-polarized detection beam, the normalized wavelength-dependent amplitude distribution of the detection beam field in the focal range can be expressed as,

\[
g_{\text{det}}(k, \rho, u) = 2 \sqrt{5(k)} \int_{r_0}^{1} r f(k, r) p_2(k, r, r_u) J_0(\rho r) \exp\left[\frac{-1}{2} i u r^2\right] dr
\]

\[
= 2 \sqrt{5(k)} \int_{r_0}^{r_u} rf(k, r) J_0(\rho r) \exp\left[\frac{-1}{2} i u r^2\right] dr
\]  

(8)

Hence, the overall normalized effective amplitude PSF of the sample arm optics then can be written as [18, 27],

\[
g_{\text{eff}}(\rho, u) = \int_{k_{\text{min}}}^{k_{\text{max}}} g_{\text{ill}}(k, \rho, u) g_{\text{det}}(k, \rho, u) dk
\]

\[
= \int_{k_{\text{min}}}^{k_{\text{max}}} \left[g(k, \rho, u)\right]^2 p_i(k, r_i) p_2(k, r_2, r_3) dk
\]  

(9)

where \( k_{\text{min}} \) and \( k_{\text{max}} \) are cut-off wave numbers.

Eq. (9) shows that the light field distribution at the focal region is solely dependent on the radii of the apertures \( p_i(k, r_i) \) and \( p_2(k, r_2, r_3) \). With the center-obscurred aperture 1 adopted in the illumination arm, a quasi-Bessel illumination beam is generated. Although Bessel beams feature a much larger DOF compared with the conventional focusing schemes [17], large sidelobes, which are only \( \sim 15 \text{dB} \) lower than the mainlobe, are introduced simultaneously [12]. Similarly, the aperture 2 adopted in the detection arm also introduces sidelobes to the sample arm optics. However, if the first sidelobe of the illumination PSF co-locates with the first minimum of the detection PSF, the first sidelobe of the sample arm PSF will be largely suppressed. In this way, both DOF extension and first sidelobe suppression can be achieved simultaneously for an OCT system.

2.2 Numerical simulation

We conducted numerical simulations to search for the optimal radii \( (a_0, r_1, r_2 \text{ and } r_3) \) and found that the first sidelobe of the illumination PSF co-locates with the first minimum of the detection PSF when \( r_2 = r_3 = 0.6 \) and \( r_3 = 0.4 \), respectively for \( a_0=1 \) (We kept \( r_1 = r_2 \) for ease of OCT experimental implementation in Section 3. However, for other values of \( a_0, r_1, r_2 \text{ and } r_3 \anela also be found for sidelobe suppression). The following parameters were adopted in the simulations: (1) a typical broadband light source has top-hat spectral intensity distribution; (2) the center frequency of the light source is \( \lambda = 810 \text{ nm} \) with a full-width at half maximum (FWHM) bandwidth of 110 nm; (3) the numerical aperture of the fiber \( NA_f = 0.125 \) (relative to \( a_0=1 \)). We simulated the normalized intensity distribution of the sample arm optics with the designed apertures adopted, and compared the proposed dark-field focusing scheme with the commonly used full-aperture scheme and the previously reported annular-aperture bright field focusing scheme (Fig. 2).

In order to demonstrate the advantages of the proposed technique, we consider four focusing schemes: a full aperture scheme (FA-OCT, Fig. 2(a)); an annular aperture scheme with aperture 1 in both illumination and detection path (BF-OCT, Fig. 2(b)); an annular aperture scheme with aperture 2 in both illumination and detection path (Fig. 2(c)); and an annular aperture scheme with aperture 1 in the illumination path and aperture 2 in the detection path (DF-OCT, Fig. 2(d)). Simulation results show that a DOF gain of 4.2 can be
achieved compared with the FA-OCT system of equal lateral resolution (Fig. 2(a)). In this work, we define DOF as 2 times the distance at which the $1/e^2$ beam waist increased by a factor of $\sqrt{2}$ according to Rayleigh range criterion [12]. It is expected that sidelobes are pronounced in the annular aperture schemes with the first sidelobe of -9.3 dB (Fig. 2(b)), and -8.7 dB (Fig. 2(c)), respectively. In our proposed DF-OCT scheme (Fig. 2(d)), the sidelobes of all orders within the simulated field are below -12.2 dB due to a first sidelobe suppression ratio of 2.9 dB and 3.5 dB, respectively. The sidelobe suppression effect by using a combination of the two apertures can be further demonstrated in lateral profiles (Fig. 3).

Fig. 2. Normalized intensity distributions in focal region of (a) a full aperture system, (b) annular aperture system with aperture 1 in both illumination and detection paths, (c) annular aperture system with aperture 2 in both illumination and detection paths, and (d) annular aperture system with aperture 1 and aperture 2 in illumination and detection path, respectively.
3. Experiment setup

We constructed a dark-field OCT system to verify our theoretical predictions experimentally (Fig. 4). A superluminescent diode array (Superlum Broadlighters D-810-HP) with a center wavelength at 810 nm and a FWHM bandwidth of 100 nm was employed as the light source of the DF-OCT system. The output power was 8.62 mW. The generated light was collimated by a lens L1 (Cat# 378-823-5, M Plan APO 10x, Mitutoyo Inc.) first, and then was split by a 45° rod mirror RM1 (#54-092, Φ = 2 mm, Edmund Optics Inc.) with the circular portion at the center directed to the reference arm while the remaining annular portion to the sample arm. The annular beam coupled to the sample arm was again cropped by an aperture stop (diameter Φ = 5 mm), and then center-obscured by another 45° rod mirror RM2 (#54-094, Φ = 3 mm, Edmund Optics Inc.) before it was directed to a pair of galvo scanners (GVSM002/M, Thorlabs Inc.) and an objective lens L4 (AC127-025-B-ML, Thorlabs Inc.). The light power on the sample was around 1.31 mW.

The beam directed to the reference arm firstly passed through a 4-f system consisting of lens L2 and L3 (AC127-025-B-ML, Thorlabs Inc.) to balance the dispersion caused by the objective lens. It was then guided to a third rod mirror RM3 (#54-092, Φ = 2 mm, Edmund Optics Inc.) to combine with the signal beam backscattered from the sample. Finally, the combined beam was focused by a lens L5 (Cat# 378-823-5, M Plan APO 10x, Mitutoyo Inc.) into a single mode fiber (780-HP, Nufern) to the spectrometer. In the constructed DF-OCT system, the aperture stop AS together with rod mirror RM2 acted as the illumination pupil filter, while the rod mirrors RM2 and RM3 together acted as the detection pupil filter. The shapes and the radii of these two filters were shown in Fig. 4(a).

The spectrometer consisted of a diffraction grating (1200 l/mm @ 830 nm, Wasatch Photonics Inc.), a camera lens (Nikon AF Nikkor 85 mm f/1.8D), and a line scan camera (E2V, AviVDA EM4). The detected signal was digitized at 12-bit digital resolution, and then transferred to a computer through camera link cables and an image acquisition card (KBN-PCE-CL4-F, Bitflow Inc.). In the experiments, the camera and the galvo scanners were synchronized by a triggering signal generated by the computer. The effective camera pixel number was 868. The spectrometer efficiency, including the grating diffraction efficiency, sensor quantum efficiency, and camera lens efficiency, was measured to be 0.376. The line
rate and the exposure time of the camera were set to be 10 kHz and 97.7 μs, respectively. The experimental axial and lateral resolutions of the DF-OCT system were measured to be 3.3 μm and 4.1 μm respectively, which match well with their corresponding theoretical values of 2.9 μm and 3.9 μm.

Fig. 4. Experimental configuration of the proposed DF-OCT imaging system. L1-L6: lens. RM1-RM3: rod mirror. M1-M2: mirror. AS: aperture stop. SMF: single-mode-fiber. (a) The geometries of the dark-field illumination beam, illumination and detection pupil filters.

Fig. 5. Two OCT systems constructed for performance comparisons. (a) Full aperture OCT (FA-OCT) system. (b) Bright field OCT (BF-OCT) apodized with annular aperture 1.

4. Results

4.1 Focal depth extension

To assess the performance of the constructed DF-OCT system, a full aperture OCT system (Fig. 5(a)) and a bright field OCT system (Fig. 5(b)) with aperture 1 in both illumination and detection paths were constructed for comparison. The light source, spectrometer settings, illumination beam diameter, and objective lens were the same for these three systems.

To demonstrate the DOF extension, we used the agarose solution (Cat#PC0701-500G, Vivantis Inc., ~0.5%) of polystyrene microbeads (Cat # SIGMA/LB8-2ML, SIGMA Inc., Dia. 800 nm, ~0.1 vol.%) to characterize the focusing performances. Figs. 6(a) and 6(b) present the cross-sectional images acquired using the FA-OCT and the DF-OCT systems, respectively,
with capturing rate of 20 frames per second (fps). Each image covers a range of 82 µm × 775 µm with 393 lateral × 744 axial pixels (Width × Depth). The axial scatter plots of the normalized intensity of a large number of microbeads scatterings for the two systems were plotted in Fig. 6(c) and 6(d), respectively. The dashed red curves are Gaussian-fits of the assumed on-axis irradiance profiles to a subset of the microbeads cloud comprising only the strongest signals. Results demonstrate that the proposed DF-OCT system increased the DOF by factors of ~3 and 1.1 compared with the FA-OCT and BF-OCT systems respectively.

Fig. 6. Real-time tomograms of 800 nm latex calibration beads acquired with the FA-COT and the DF-OCT systems, respectively. Cross-sectional images of the microbeads agarose solution are grabbed with (a) FA-OCT system and (b) DF-OCT system. Red bars in the images indicate the DOF. The axial scatter plots of the normalized intensity of microbeads scatterings are shown in (c) for FA-OCT system and (d) for DF-OCT system. The dashed red curves are Gaussian-fits of the assumed on-axis irradiance profiles to a subset of the microbeads cloud comprising only the strongest signals.
4.2 Sidelobe Suppression

To test the sidelobe suppression effect of the constructed DF-OCT system, we used the microbeads solution to characterize its focusing performance and compared it with that of the BF-OCT system. In order to observe the sidelobes more clearly, we used the aqueous solution of polystyrene microbeads (Cat # SIGMA/LB8-2ML, SIGMA Inc., Dia. 800 nm, ~0.1 vol.%). Figure 7(a) shows the real-time tomograph acquired using the BF-OCT system, whereas Fig. 7(b) presents the image acquired using the DF-OCT system. Results demonstrate that, compared with the BF-OCT system, lateral sidelobes of the image are largely suppressed with the DF-OCT system.

Fig. 7. Sidelobe suppression with the constructed dark-filed OCT (DF-OCT) system compared with that of the constructed bright field OCT (BF-OCT) system. Real-time tomograph of 800nm microbeads are acquired with (a) BF-OCT system and (b) DF-OCT system. (c) Lateral intensity profiles of microbead images that are acquired using BF-OCT and DF-OCT setups, and are compared to the simulation results.
We have also measured the lateral intensity profiles of microbead images that are acquired using BF-OCT and DF-OCT setup (Fig.7(c)). Experimental results demonstrated that the first sidelobe of the DF-OCT system (red solid line) was 3.1 dB smaller than that of the BF-OCT system (Magenta dash-dotted line). Although the lateral resolution was slightly degraded and the amplitudes of higher order sidelobes were elevated in the DF-OCT case (dashed blue line) with respect to the case of BF-OCT (dark dotted line), such effects were secondary since the first sidelobe is the most prominent artifact in OCT images [12]. The measured results agreed well with the numerical simulation results except for the lateral positions of peaks and valleys. Such variances could be caused by the difference between the nominal and actual fiber NA.

4.3 Sensitivity

It is not straightforward to measure the sensitivity of the constructed DF-OCT system due to the dark-field configuration. However, since the DF-OCT and the FA-OCT systems shared the same spectrometer settings and reference input, it is reasonable to assume that the noise terms are the same for the two systems. Therefore, the sensitivity difference between the two systems should come from their measured signal intensity difference of the sample.

With a sample power of 2.9 mW, the sensitivity of the FA-OCT system was measured to be 102.6 dB. As the measured signal intensity of the FA-OCT system outperformed that of the DF-OCT system by ~11.6 dB for the same microbead sample, we estimated the sensitivity of the DF-OCT system to be 91 dB.

5. Summary

In conclusion, we have developed a new scheme by utilizing two pupil filters to extend DOF while suppress the first sidelobe for SD-OCT systems. Numerical simulations were carried out to verify the feasibility of such scheme theoretically. It is predicted that a DOF gain of 4.2 can be achieved compared with a full-aperture imaging system, while a suppression ratio of 2.9 dB for the first sidelobe could be achieved compared with a bright-field imaging system. The theoretical predictions were further verified by experimental results. We constructed a DF-OCT system to extend the DOF by about three-fold compared with a full-aperture OCT system, and suppress the first sidelobe by 3.1 dB compared with a bright-field annular aperture OCT system. The compromise for the extended DOF, however, is an ~11.6 dB drop in sensitivity compared with FA-OCT. The proposed scheme can also be extended to the cases of phase pupil filters and axicon based focus engineering schemes where sidelobe artifacts are also big issues.

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