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Abstract. We present a calibration protocol to obtain the alignment factors of a custom-made spectrometer and the nonlinear fitting function between the measured CCD pixel domain and the wavelength domain to apply to the spectral-domain optical coherence tomography (SD-OCT) using fiber Bragg gratings. We have used five gratings with different center wavelengths covering the broadband source spectral range. All have a narrow spectral bandwidth (0.05 nm) and the same reflectivity (92%) to calibrate and align the custom-made spectrometer. The implemented SD-OCT system following the proposed protocol showed the alignment factors as 44.37 deg incident angle, 53.11 deg diffraction angle, and 70.0-mm focal length. The spectral resolution of 0.187 nm was recalculated from the alignment factors. © 2011 Society of Photo-Optical Instrumentation Engineers (SPIE). [DOI: 10.1117/1.3552602]

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Fourier-domain optical coherence tomography (FD-OCT) has shown a faster measurement speed than traditional time-domain OCT. FD-OCT technology has two primary types of implementation depending on the optical source and the photodetector. The first one is based on a high speed wavelength swept fiber laser, a balanced receiver, and all optical fiber components so that this type of FD-OCT is realized without tricky optical alignment.¹ The second one is called spectral-domain optical coherence tomography (SD-OCT) and utilizes a broadband source and a spectrometer configuration.² However, the spectrometer of SD-OCT requires very tight design conditions

of light incidence angle into the diffraction grating, the diffraction angle, and the focal length between a focusing lens and CCD array. Due to the difficulties of finding the optimal alignment, the point spread function and final image qualities have been used as general guidelines to gauge the performance of SD-OCT. Moreover, advanced SD-OCT systems become more complex in their construction to increase functionality and performance. For example, polarization sensitive OCT based on two spectrometers^{2,3} and OCT with a linear-in-wavenumber spectrometer have been reported recently.⁴ However, as the complexity of the SD-OCT system increases, the optimization and the calibration of the alignment factors for its spectrometer become progressively more difficult.

Three crucial design parameters of the spectrometer for SD-OCT are the light incident angle, θ_i , the diffraction angle, θ_o , and the focal length of the focusing lens between the diffraction grating and the CCD array, f .^{4,5} The choice of these three parameters ultimately determines the spectral resolution of the SD-OCT system. However, the evaluation of the performance of a custom-made spectrometer is rather challenging since we need to pursue not only a high spectral resolution but also the reduction of nonlinearity between the measured CCD pixel number and the matched wavelength. A multiwavelength lamp with low-pressure gas discharge lines of HgAr, Neon, Ar, and Zinc was used to calibrate an optical spectrometer in the previous works.^{2,5} It is impossible for the method to control the peak intensity and the spectral peak wavelengths matched with wavelength range of spectrometer.

We present a protocol for SD-OCT using fiber Bragg gratings (FBGs) to alleviate these difficulties in the alignment process and evaluation of the spectrometer performance. The advantages of FBGs are the precise position of center wavelength, narrow spectral bandwidth less than 0.1 nm, and high reflectivity over 90%.^{6,7} Thanks to athermal packaging methods, the fiber grating has very little temperature variation in the operating temperature range.⁸ Recently, fiber gratings have been applied to OCT in developing an all optical fiber delay line⁹ and triggering a high speed digitizer synchronized with a wavelength swept fiber laser.¹⁰

In this paper, we have used five different FBGs with a narrow spectral bandwidth (0.05 nm) and the same reflectivity (92%) to calibrate and align the custom-made spectrometer for the SD-OCT system operating in the 1300-nm wavelength range. Finally, we present the calibration and characterization protocol to obtain the alignment factors of the custom-made spectrometer and the nonlinear fitting function between the measured CCD pixel domain and the wavelength domain to apply to SD-OCT.

Figure 1 depicts the schematic of the SD-OCT system with the calibrating FBGs (O/E Land Inc.) with different center wavelengths ($\lambda_1 = 1269.4$ nm, $\lambda_2 = 1299.5$ nm, $\lambda_3 = 1309.4$ nm, $\lambda_4 = 1329.5$ nm, and $\lambda_5 = 1359.4$ nm). Each FBG has almost the same spectral bandwidth of ~ 0.05 nm which is narrower than the designed spectral resolution of the SD-OCT system. The selection of the grating wavelengths depends on the center wavelength of the broadband source and a spectrometer design. We assumed that the broadband source envelope had a Gaussian spectrum. To make the bandwidth measured by CCD broad effectively, we assigned the center pixel of CCD to the center

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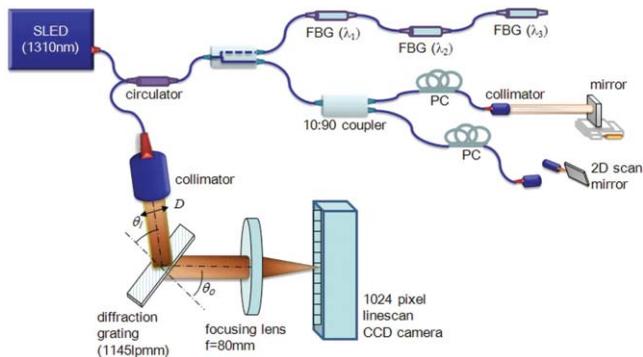


Fig. 1 Schematic of the SD-OCT system with the calibrating FBGs. SLED: superluminescent diode, FBG: fiber Bragg grating, PC: polarization controller.

wavelength of source. If a grating wavelength is the same as the center wavelength of the source, the spectral line is helpful to guide spectrometer alignment. We assigned a recognizable wavelength of the first and fifth gratings matched with both edges of the source spectrum. The wavelengths for the second and the fourth gratings were assigned to those matching with the source wavelengths with 90% intensity level. The FBGs were packaged with a quartz substrate base and stainless tubing to prevent the resonance wavelength change. The output of a broad-bandwidth superluminescent diode (SLED; $\lambda_c=1310$ nm, $\Delta\lambda=89$ nm, and $P_{out}=9$ mW) is interfaced with a compact, fiber-based SD-OCT system. A fiber pigtailed circulator is used at the input to minimize back-reflections to the SLED and to maximize amplitude of the interference signals. A broad-bandwidth 10:90 fused fiber coupler is used as the core of the SD-OCT system. The reference arm of the system is comprised of a collimator and a mirror mounted on a translation stage. The sample arm of the SD-OCT system is a two-dimensional galvo-scanning mirror with achromatic doublet focusing lens to reduce lateral and transverse aberrations. The interference signal is detected with a custom-made spectrometer.

The proposed calibration and characterization protocol for the SD-OCT spectrometer consists of five flow steps. Step 1 of the procedure is to find the three design factors (θ_i , θ_o , and f) and to align the optics along following the design factors. The factors satisfy the wavelength range on the one CCD pixel ($\delta\lambda_c$) and the spectral resolution of the diffraction grating ($\delta\lambda_g$), which are given by:

$$\delta\lambda_c = dp\cos\theta_o/mf, \quad (1)$$

$$\delta\lambda_g = \lambda d\cos\theta_B/mD, \quad (2)$$

where p is the pitch of the CCD array, m is the diffraction order, and D is the incidence beam diameter, respectively.¹¹ In the experimental setup, the collimator had a 6.6-mm beam diameter and 0.24 numerical aperture to obtain a Gaussian intensity spot diameter of the optical source smaller than the CCD pixel width. The diffraction grating (grating period of $d = 1145$ lp/mm) had an optimized incident angle of 48.59 deg at the center wavelength of 1310 nm. The achromatic doublet imaging lens with 80-mm focal length was behind the grating. The spectrometer was interfaced to a 1024 pixel line scan InGaAs CCD camera (SUI, Goodrich Corp.) with a 15 mm array pitch and a 47-kHz readout

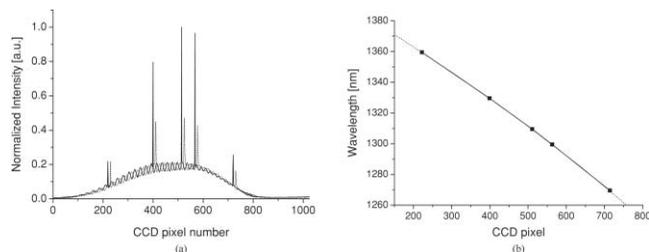


Fig. 2 (a) Unprocessed measured data on the spaced pixels for the FBGs before (dotted line) and after (solid line) the fine tuning of the custom-made spectrometer. (b) Absolute wavelength calibration between CCD pixel domain and wavelength domain [wavelength fitting curve from the grating equation (dashed line) and third order polynomial fitting curve (dotted line)].

rate. The data was transferred to a personal computer via a Camera Link connection. The expected spectral resolution was 0.18 nm ($\delta\lambda_c = 0.18$ nm and $\delta\lambda_g = 0.12$ nm).

Step 2 is to align the spectrometer in a way that the center wavelength ($\lambda_o=1310$ nm) matches the center pixel of the CCD camera.

Step 3 is to find the single pixel showing the reflection signal of each narrow FBG and to compare the reflectivity distribution of the FBGs with the envelope of the optical source. We could adjust the location of the focal plane of the focusing lens by looking at the pixel number covered with the single FBG's spectral bandwidth and the relative reflectivity change of the FBGs. Figure 2(a) shows this procedure before (dashed line) and after (solid line) the fine optics tuning of the custom-made spectrometer.

Step 4 is to determine a nonlinear fitting function between the CCD pixel domain and the wavelength domain using the grating equation²

$$\lambda_j = d \left(\sin\theta_i + \sin \left\{ \tan^{-1} \left[\frac{p}{f} \left(\frac{n}{2} - j - 1 \right) \right] + \theta_o \right\} \right), \quad (3)$$

where λ_j is the wavelength matched with the j th pixel of the CCD array and n is the total number of CCD pixels (1024). The fitting function from the grating equation was compared to the polynomial fitting functions (second order and third order). Figure 2(b) shows the wavelength calibration between the spaced pixels of the linescan camera and the converted wavelength domain [wavelength fitting curve from the grating equation (dashed line) and third order polynomial fitting curve (dotted line)]. The adjusted R -square values of the fitting functions are 0.9999 (wavelength fitting curve from the grating equation using three FBGs), 0.9999 (second order polynomial fitting function using three FBGs), and 1.0 (third order polynomial fitting function using four FBGs with additional 1329.52 nm FBG).

Finally, the alignment factors were obtained from the fitting function at step 5. We calculated the alignment factors as 44.37 deg incident angle, 55.11 deg diffraction angle, and 70.01-mm focal length and then recalculated the spectral resolution of 0.187 nm, which allowed the SD-OCT measurement range of 3 mm. From the calculated factors, we can easily determine how close

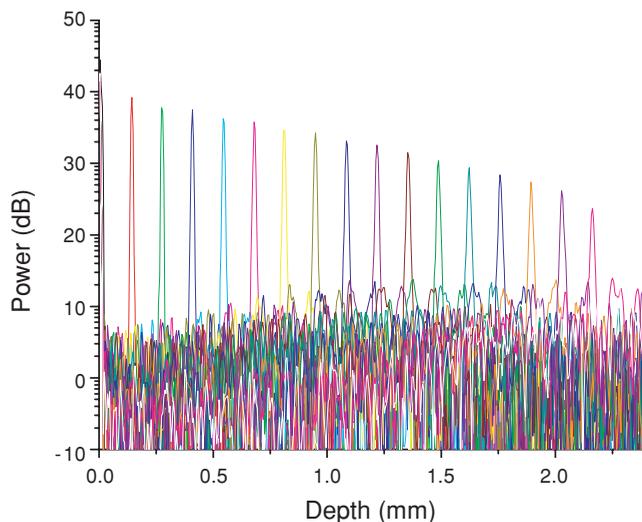


Fig. 3 Point spread functions of the OCT system in the different depths.

we are to the expected design factors and what to do for the feedback process.

The SD-OCT performance measurements were conducted at a speed of 47k A-scans/s with 14 ms exposure time. A maximum signal-to-noise ratio of 103.24 dB was achieved with 8.97-dB reference attenuation and 26.27-dB sample arm attenuation. To evaluate the performance of the SD-OCT system, we measured the point spread functions of the SD-OCT system. The axial resolution was 8 mm in air. The point spread functions showed the sensitivity fall-off of 7.1 dB/mm as shown Fig. 3.

The tomograms of IR card and *in vivo* human fingerprint were also acquired with an image size of 512×512 pixels as shown in Fig. 4.

In summary, we proposed the calibration and characterization protocol to define the alignment factors for a custom-made spectrometer in a SD-OCT system using FBGs. The five different FBGs, covered the broadband source wavelength range with

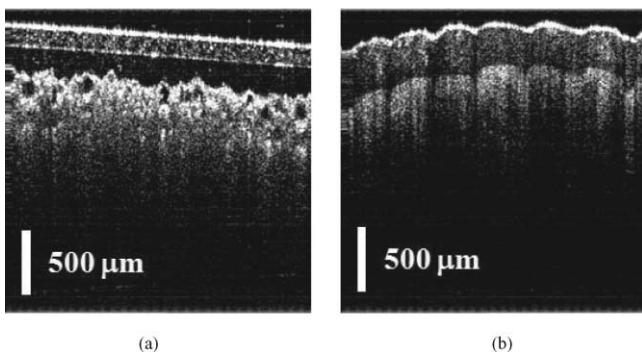


Fig. 4 (a) OCT image of the IR card and (b) fingerprint.

0.05-nm spectral bandwidth and 92% reflectivity to align the spectrometer. And we obtained the nonlinear fitting function between the pixel domain of the CCD camera and the wavelength domain. The implemented SD-OCT followed the proposed protocol. We obtained the alignment factors: incident angle of 44.37 deg, diffraction angle of 55.11 deg, and focal length of 70.0 mm, and recalculated the spectral resolution of 0.187 nm. The proposed protocol is expected to alleviate difficulties in alignment process and evaluate spectrometer performance for the multifunctional and specially designed SD-OCT system.

Acknowledgments

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