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Optimization of linear-wavenumber spectrometer for high-resolution spectral domain optical coherence tomography

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ABSTRACT

Nonlinear detection of the spectral interferograms in wavenumber (k) space degrades the depth-dependent signal sensitivity in conventional linear-in-λ spectrometer based spectral domain optical coherence tomography (SDOCT). Linear-k spectrometer enables high sensitivity SDOCT imaging without the need of resampling the digitized non-linear-in-k data. Here we report an effective optimization method for linear-k spectrometer used in a high-resolution SDOCT system. The design parameters of the linear-k spectrometer, including the material of the dispersive prism, the prism vertex angle, and the rotation angle between the grating and prism, are optimized through the numerical simulation of the spectral interference signal. As guided by the optimization results, we constructed the linear-k spectrometer based SDOCT system and evaluated its imaging performances. The axial resolution of the system can be maintained to be higher than 9.1 μm throughout the imaging depth range of 2.42 mm. The sensitivity was experimentally measured to be 91 dB with −6 dB roll-off within the depth range of 1.2 mm.

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1. Introduction

Spectral domain optical coherence tomography (SDOCT) is a high-speed volumetric biomedical imaging modality for biological research and clinical application [1,2]. It enables tomographic imaging with micrometer-scale resolution and millimeter-scale depth range. In SD-OCT the sample is illuminated by a broadband light source, and the spectrum of the interference light between the light returned from the sample and a reference mirror is detected by a grating spectrometer. Conventionally, the grating spectrometer is comprised of a diffraction grating, a focusing lens, and a line-scan camera. According to the grating equation the diffraction angle from the diffraction grating is approximately linearly related to the optical wavelength. Thus the distribution function of the light spectrum at the line-scan camera is nonlinearly dependent on the wavenumber (k). The non-linear-in-k characteristic of the conventional spectrometer induces two effects to the SDOCT imaging. Firstly the axial point spread function will be broadened if the non-linear-in-k spectral interference data is Fourier transformed (FT) directly. Secondly the sensitivity will be rolled off more quickly in depth since the wavenumber bandwidth integrated by an individual pixel is nonuniform [3].

To solve the non-linear-in-k issue numerical resampling of the spectral interference data from λ-space to k-space is commonly required prior to FT [4]. This resampling process is usually computationally complex for CPU processing. Although this process can be accelerated by utilizing GPU processing, the sensitivity roll-off still cannot be improved. An alternative method is to use a linear-k spectrometer, which not only can directly obtain the linear-in-k data, but also can improve the sensitivity roll-off performance simultaneously. Hu et al. first introduced the linear-k spectrometer into SDOCT system using a customized isosceles dispersive prism made of BK7 glass [5]. They used the derivatives of the output angles from the prism with respect to wavenumber to maximize the linearity of the wavenumber. In their design of the linear-k spectrometer, the only optical parameter considered was the vertex angle of the isosceles prism. Gelikonov et al. presented a linear-k spectrometer not only considering the prism vertex angle but also the tilt angle between the incident plane of the prism and the grating plane. Furthermore, they suggested using the relative deviation of the wavenumber as a criterion for estimating the level of residual nonlinearity of the wavenumber [6]. Thereafter Watanabe et al. optimized the prism material and the tilt angle between the grating and prism [7]. Accounting for the trigonometric relationship they used

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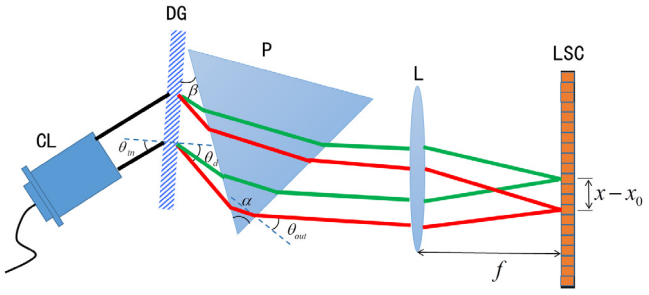

Fig. 1. Schematics of the linear-k spectrometer. CL: fiber collimator; DG: transmissive diffraction grating; P: dispersive prism; L: focusing lens; LSC: line scan camera.

the standard deviation of the derivatives of the pixel coordinates with respect to the wavenumber as the linear-k optimization criterion. Sang-Won Lee et al. performed a numerical simulation to find a set of the optimal design parameters including the number of grooves per mm of the diffraction grating, the material of the dispersive prism, and the rotation angle between the grating and the dispersive prism for a linear-k spectrometer to achieve ultrahigh axial resolution [8]. As in [5] the optimal angles and the material of the prism were also optimized by minimizing the standard deviation of the derivatives. Recently, Lan et al. reported a linear-k spectrometer for ultrahigh resolution SDOCT system. They used quantitative ray tracing technique to calculate the root-mean-square deviation of the output angle of 11 discrete wavenumbers from the prism, which was used as a criterion for evaluating the linearity of the wavenumber in the linear-k spectrometer [9].

In this paper we present an alternative optimization criterion to optimize design parameters of a linear-k spectrometer, including the prism vertex angle, the material of the dispersive prism and the rotation angle. By incorporating these design parameters into the formula relating the wavenumber and the pixel coordinate, the spectral interference signal and its point spread function (PSF) can be numerically simulated. We propose to use the full width half maximum (FWHM) value of the PSF as the criterion to optimize the design parameters. After constructing the linear-k spectrometer based on the optimized design parameters, its performance is evaluated by measuring the axial resolution and the sensitivity of the system and comparing the experimentally measured results with the theoretical values. Finally we demonstrate the *in vivo* OCT image of human finger skin obtained by the linear-k spectrometer based SDOCT system.

2. Method

The schematic of a linear-k spectrometer is shown in Fig. 1. It consists of a collimator CL, a diffraction grating DG, a dispersive prism P, a focusing lens L, and a line-scan camera LSC with evenly-spaced pixels. As shown in Fig. 1 the coordinate of the center of each pixel at the camera is described as x. According to the ray tracing formulas, the output angle from the prism θ_{out} corresponding to a specific pixel with coordinate x can be expressed as

$$\theta_{\text{out}} = \arctan\left(\frac{x - x_0}{f}\right) + \theta_0, \tag{1}$$

where f is the focal length of the focusing lens, and θ_0 is the output angle from the prism P corresponding to the central pixel location x_0.

Given a set of the design parameters of the linear-k spectrometer (α, β, n), using the ray tracing equations, the diffraction angle θ_d from the diffraction grating corresponding to the angle θ_{out} can be inversely derived as

$$\theta_d = \arcsin\left[n \sin\left(\alpha - \arcsin\left(\frac{\sin\left(\theta_{out}\right)}{n}\right)\right)\right] - \beta, \tag{2}$$

where α is the vertex angle of the prism, β is the rotation angle between the grating plane and the incident plane of the prism, and n is the material refractive index of the prism.

The incident angle illuminating the diffraction grating θ_{in} is set to the blaze angle for the best diffraction efficiency,

$$\theta_{in} = \sin^{-1}\left(\frac{\lambda_{kc}}{2d}\right), \tag{3}$$

where λ_{kc} is the optical wavelength corresponding to the center wavenumber, and d is the grating constant. Substituting Eqs. (1)–(3) into the grating equation, the wavenumber recorded by a pixel of coordinate x can be expressed as

$$k = \frac{2\pi}{d \sin\left(\arcsin\left(n \sin\left(\alpha - \arcsin\left(\frac{\sin\left(\arctan\left(\frac{x-x_0}{f}+\theta_0\right)\right)}{n}\right)\right)\right) - \beta\right) + \frac{\lambda_{kc}}{2}}. \tag{4}$$

According to Eq. (4) a specific wavenumber distribution function $k\,(x)$ can be numerically simulated once a set of the design parameters is designated. Then the spectral interference signal corresponding to a specific depth can be simulated by multiplying a Gaussian power spectral density function with a cosine function containing the wavenumber distribution function. The spectral interference signal can be expressed as

$$I\,(k) = S\,(k) \cos\left(2kz\right), \tag{5}$$

where z is the depth coordinate, and k is a specific wavenumber distribution function simulated by Eq. (4). The PSF can be obtained by taking Fourier transform of the spectral interference signal. Then we can calculate the FWHM of the PSF, i.e. the axial resolution. The axial resolution is used as the optimization criterion for the design parameters of the linear-k spectrometer. By finely tuning the design parameters the minimum FWHM value can be obtained, from which we can get the optimal design parameters.

To assess the linearity of the wavenumber of the optimized linear-k spectrometer we also calculate the relative deviation function $\varepsilon\,(x)$. It characterizes the relative deviation of the wavenumber of a specific wavenumber distribution function $k\,(x)$ from the ideal linear wavenumber distribution function $k_1\,(x)$ [6]. The ideal linear wavenumber distribution function $k_1\,(x)$ is defined as

$$k_1\,(x) = k_c + \frac{\Delta k}{\Delta x}\left(x - x_0\right), \tag{6}$$

where k_c is the center wavenumber, and Δx is the spatial range of the pixels covering the detectable wavenumber range Δk. The relative deviation function $\varepsilon\,(x)$ is defined as

$$\varepsilon\,(x) = \left(k\,(x) - k_1\,(x)\right)/\Delta k, \tag{7}$$

where Δk is the detected wavenumber range. Thus a metric $\delta\varepsilon$ giving the numerical estimate of the nonlinearity of the distribution $k\,(x)$ can be expressed as

$$\delta\varepsilon = \left[\varepsilon\,(i) - \varepsilon\,(j)\right]_{\max}, \tag{8}$$

where i and j are arbitrary numbers corresponding to the pixel numbers ($0 \le i, j < N$). N is the total number of the detection pixels. According to the Nyquist sampling theory, the detectable maximum frequency of the spectral interference signal satisfies the relationship $f_{\max} = N/2$. The resolution distortion caused by the nonequidistance of the wavenumber distribution will be insignificant if the deviation which gives the numerical estimate of the nonlinearity of wavenumber distribution is less than spectrum sampling interval. Thus, a direct condition on the permissible $\delta\varepsilon$ in the case of Gaussian spectrum can be represented as $\delta\varepsilon \le 1/N$ [6].

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