Spectrometer Design for an 840 nm Spectral Domain Optical Coherence Tomography System

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Abstract. In this paper, the design and performance of a custom-built spectrometer for Spectral Domain Optical Coherence Tomography (SD-OCT) imaging for a near-infrared wavelength range centered around 840 nm is presented. Two configurations of spectrometers based on reflective and transmission type grating and achromatic doublet lens were analyzed and the spectrometer performance characteristics are studied. The spectrometer is designed to work best with a light source whose wavelength is 840 ± 46 nm. A line scan camera captures multiple wavelengths simultaneously. In order to achieve higher resolution and imaging depth, a 2048-pixel array linear line scan camera from Basler was chosen. The line scan camera's detector has a length and width of 14.3 mm and 7 µm, respectively. The spectrometer design was simulated using Zemax software and the design parameters are described in this paper.

Keywords: spectrometer, Zemax simulation, transmission type grating, reflective type grating.

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1 Introduction

Optical coherence tomography (OCT) provides a high-resolution (1–15 µm) cross-sectional imaging of biological tissues which makes it a powerful tool in clinical diagnosis. The depth of imaging is restricted to 1~2 mm due to optical scattering in tissues [1].

In most of the commercial OCT systems, spectral domain OCT (SD-OCT) is employed due to high-speed acquisition capability. This technique is based on Michelson interferometer, the broadband light source in the near infrared region is used as a source. Using a beam splitter the light is made to illuminate two arms, one with the sample and other with reference mirror. The backreflected light from both the arms interfere at beam splitter and moves to the spectrometer. Spectrometer records intensity of all wavelengths. The recorded spectral information in converted to k-space and then an inverse Fourier transform is applied to extract depth versus intensity profile also known as A-scan [2].

The spectrometer plays a major role in the quality of image and the depth of imaging. The spectrometer is typically made up of a diffraction grating, focusing lens and single array CCD camera or detector. In order to improve the SD-OCT performance, it is crucial to assess the spectrometer's parameters. The choice of light source (central wavelength and spectral width), the focusing optics in the spectrometer and the detector parameters affects the spectrometer performance. For SD-OCT imaging systems, numerous spectrometer designs and arrangements have been put out thus far [3–5].

A prism is used to linearize spectrum data in wavenumber followed by grating [6]. With this method, the processing time is reduced, the depth-dependent sensitivity fall-off is improved and numerical interpolation is eliminated. In addition to using a prism, it can be created using reflecting optics, which removes the chromatic aberration and improve quality of image. Kamal et al. presented a spectrometer for OCT imaging with high quality which takes the chromatic aberration in account along with optical resolution and detector array resolution. A planer reflecting grating, an off axis parabolic cylindrical mirror and a CCD array detector make up the proposed imaging spectrometer. Reflective optics focusing improves the clarity of the spectrometer [7].

Three optical frequency windows, 840, 1050, and 1310 nm, are frequently utilized in OCT imaging because

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of the technological limits of detectors and the availability of light sources. For anterior segment imaging, practical 840 nm hybrid retinal/corneal Fourier-domain OCT systems are fast and sensitive enough.

The choice of source wavelength in the OCT system depends on the application that it is being considered for. An OCT system's axial resolution is inversely related to the light source's bandwidth and proportionate to the square of the centre wavelength. Therefore, the wider bandwidth and shorter wavelength offer superior resolution. For instance, in retinal imaging, a spectral window centred at 840 nm with a bandwidth of 40 nm is commonly utilised to attain maximum axial resolution (~7 μm). Additionally, water strongly absorbs light with a wavelength of 1310 nm, resulting in a retinal exposure that is less than 7% of the power incident on the cornea. In contrast, the retina receives practically all of the 840 nm wavelength light that strikes the eye without being absorbed. The sensitive retinal tissue is not typically exposed to 1310 nm light, hence much higher power levels can be utilized on the eye without harm. The SLED source from EXALOS (EXS210006-03) is chosen as a light source.

So, the optical design of a spectrometer for a light source centered at 840 nm with a bandwidth of 46 nm is presented in the following sections. In this work, two grating-based line scanning spectrometer models are introduced. The first is based on a reflecting grating and the second is based on a transmission grating. On the basis of their optical capabilities, the two are compared. The optical studio Zemax was used to create and implement each spectrometer.

2 Methodology

The four main parts of a conventional SD-OCT spectrometer are the beam lead (collimator), the dispersive element (diffraction grating), the collecting optics (a focusing lens), and the detector (CCD camera). Since these optics play a major role in the resolving capability of the OCT system, the detector specification is taken into account early in the spectrometer design process.

2.1 Theory and Properties

Eq. (1) illustrates the connection between the diffracted angle and the wavelength of the transmission and reflected grating

$$d[\sin(\theta_i) \pm \sin(\theta_d)] = m\lambda, \quad (1)$$

where d is the grating period, θ_d is the diffraction angle, θ_i is the incident angle, m is the diffraction order, and λ is the wavelength.

Theoretically, an SD-OCT system's axial resolution is provided by following:

$$\Delta z = \frac{2\ln 2}{n\pi}\frac{\lambda_0^2}{\Delta\lambda}, \quad (2)$$

where λ_0 is the center wavelength, n is the sample's refractive index and $\Delta\lambda$ is the optical source's bandwidth. It should be noted that the axial resolution is inversely proportional to source's bandwidth and this value is only possible if the source's complete bandwidth can be detected by the detector.

The light source in use has a bandwidth of 46 nm and a central wavelength of about 840 nm. Based on bandwidth, the spectral range between λ_{min} = 817 nm and λ_{max} = 863 nm was taken into consideration. As said, the coherence light source determines the axial resolution and is computed using Eq. (2). The theoretical axial resolution in air, taking the provided light source into account is 6.764 μm.

2.2 Detector

In order to achieve optical source-restricted axial resolution without reducing the imaging range, utilize an ideal technique such that the maximal imaging depth and axial resolution are chosen at the design stage.

The maximum imaging depth is determined by the optical source parameters and the overall detector pixel count. As a result, by choosing the pixel spacing to be half of the theoretical axial resolution, the imaging depth is improved while the axial resolution is maintained.

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$$Z_{\max} = \frac{1}{4}\frac{\lambda_0^2}{\Delta\lambda}N, \quad (3)$$

where λ_0 is the central wavelength, $\Delta\lambda$ is the spectral bandwidth's full width at half maximum, and N is the number of pixels of the detector. Theoretical imaging depth in air is determined to be 7 mm using the optical source parameters used and N = 2048 pixels.

2.3 Diffraction Grating

The light can be spectrally dispersed over the detector using a prism or grating. Since grating offers two unique advantages, it is typically used. It offers better resolution than prism to start. Second, this occupies lesser space in the spectrometer design. The resolution of the spectrometer is significantly influenced by the grating's characteristics. Resolving power (R), a dimensional less number that describes gratings is determined by following Eq. (4):

$$R = \frac{\lambda}{\delta\lambda} = mM, \quad (4)$$

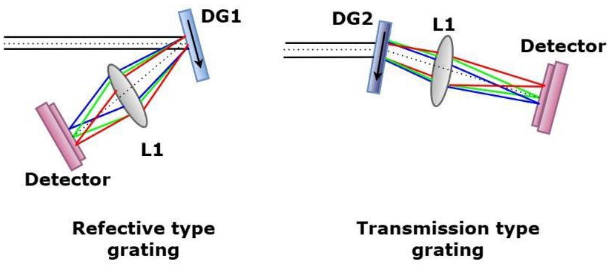


Fig. 1 Spectrometer configurations.

where M is the number of grooves illuminated on the grating, λ is the maximum wavelength, $\delta\lambda$ is the highest spectral resolution that a grating can achieve, and m is the diffraction order.

For a particular grating shape, where the scattered light returns in the same direction as the incident light ($\theta_i = \theta_d$), the efficiency is maximized. Littrow condition is the name given to this condition. As a result, the grating equation for Littrow configuration becomes as following Eq. (5):

$$[\sin(\theta_i) = \sin(\theta_d)] = \frac{m\lambda}{2d}. \quad (5)$$

2.4 Spectrometer Optical Resolution

The transmission and reflective grating-based spectrometer design was created using the Zemax software. The light source used in the simulation is a Super-Luminescent Light Emitting diode (SLED) with a central wavelength of 840 nm and a bandwidth of 46 nm (Exalos EXS210006-03).

Fig. 1 represents the schematic diagram of both spectrometer configurations. The achromatic doublet lens with a focal length of 100 mm is used for focusing the rays from the grating. A commercial Basler ral2048-80km line scan camera (12-bit camera, 80 kHz line rate and 2048 pixels, each of size 7 μm × 7 μm) was considered in the simulation. The optical components utilized to execute the two spectrometer design are summarised in Table 1.

In the present work, light beam of width 2 mm was used to evaluate the imaging performance. In Zemax simulation, for performance analysis three wavelengths 817 nm, 840 nm, and 863 nm are used. In the simulation, a collimated beam of diameter 2 mm is made incident on the dispersive element. The grating (DG1/DG2) separates the various wavelengths in the source spectrum and this is made incident on the line scan camera. The distance between the grating and line scan array is optimized to obtain maximum resolving power.

3 Results and Discussions

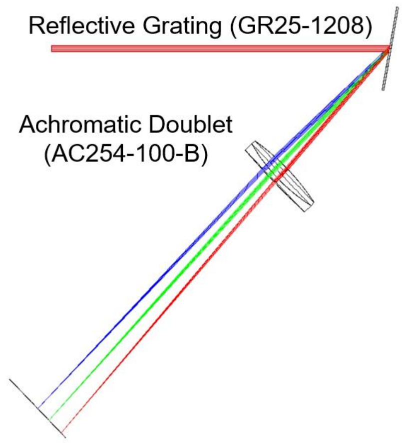
3.1 Transmission Grating

In transmission grating type spectrometer, the light incident on the grating (DG 2) is dispersed as individual wavelength at different angles as it passes through the grating. This beam is then focused onto the detector array using an achromatic doublet lens (L1). The distance between the optical components are as follows: the grating is placed at 10 mm from the point of light entry into the spectrometer, distance between the grating and the focusing lens is 10 mm and the optical distance between the lens and detector is 97.040 mm.

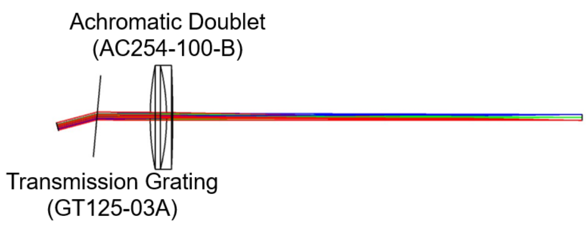
3.2 Reflection Grating

In reflection grating type spectrometer, the light incident on the grating (DG1) is dispersed as individual wavelength at different angles as it passes through the grating. This beam is then focused onto the detector array using the lens (L1). The distance between the optical components are as follows: the grating is place at 100 mm from the point of entry into the spectrometer, the distance between the grating and lens is 50 mm and the optical distance between the lens and detector is 97 mm. Fig. 2 illustrates the Zemax ray diagram for both the spectrometer design.

The 3D enclosure design of the spectrometer is designed using Autodesk Fusion 360 and the design is 3D printed using the 3D printer (Ultimaker 3). The design is made such that the grooves matches the dimension of the individual components of the spectrometer. The design and the 3D printed output is shown in Fig 3.



(a)



(b)

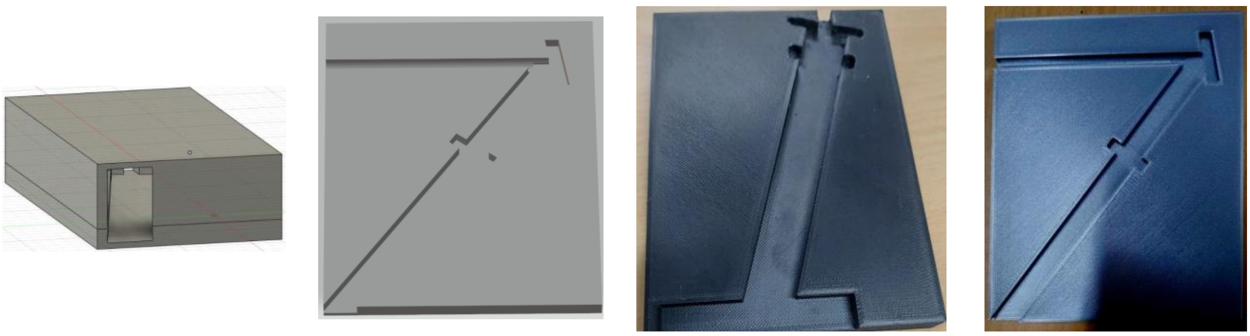
Fig. 2 Ray diagram for the (a) reflective type and (b) transmission type spectrometer design.

Table 1 The optical components utilized to execute the two spectrometer design.

Acronynm	Description	Part Number	Manufacturer
L1	Achromatic doublet Lens f = 100 mm	AC254-100-B	Thorlabs
DG1	Ruled reflective diffraction grating, 1200 grooves/mm	GR25-1208	Thorlabs
DG2	NIR Transmission grating, 300 grooves/mm	GTi25-03A	Thorlabs
Detector	Line scan camera 2048 pixel, 12 bits, line rate 80 kHz, each pixel size is 7 µm × 7 µm	racer raL2048-80km	Basler

Table 2 Evaluation of Spectrometer performance.

Sensor size (mm)	Beam diameter falling in the sensor (mm)	Number of pixels covered in detector	Resolution (nm)	Imaging depth (mm)	Sensor size (mm)
Transmission	14.3	1.434	205	0.22	0.786
Reflective		10.080	1440	0.031	5.52



(a) (b) (c) (d)

Fig. 3 The 3D design (a) transmission type (total enclosure), (b) reflective type (base) and the 3D printed output, (c) transmission type (base), and (d) reflective type spectrometers (base).

3.3 Comparison

By comparing the two spectrometric designs the refractive grating has a better spread of the wavelength in the detector. The coverage on the detector is higher in the reflective type than in the transmission type. This ensures higher resolving capacity and greater depth of imaging. The comparision of the spectrometers is described in Table 2.

4 Conclusion

The contribution of the spectrometer to SD-OCT system performance is investigated, and general design consideration for the spectrometer for an 840 nm system are outlined. The importance of spectrometer design and the impact of the selected optic source, central wavelength, bandwidth, grating and line scan camera have been studied using Zemax Optic Studio and its performance has been evaluated. It is found that the reflective type grating has a better spread on the detector and hence results in a higher spectral resolution of 0.031 nm/pixel in comparison to the transmission type grating which gives a resolution of 0.22 nm/pixel. The theoretical imaging depth for reflective type is 5.52 mm and that of transmission type is 0.786 mm. Thus the reflective type is found to be a better choice for SD-OCT system.

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Disclosures

The authors declare no conflict of interest.

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